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EAGLE ENGINEERING
FINAL REPORT

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LIQUID ROCKET BOOSTER STUDY
FINAL REPORT

GENERAL DYNAMICS
Space Systems Division

NSTS Liquid Rocket Booster

General Dynamics Corporation

Task I

Vehicle Systems Effects

Prepared By

Eagle Engineering Incorporated

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Introduction

The Liquid Rocket Booster study conducted by The Space Systems Division of General Dynamics Corporation was intended to identify concepts for Liquid Rockets to replace the current NSTS Solid Rocket Boosters with minimum impact to the on-going Shuttle Program and increased reliability and performance capability. Additional objectives of the study were to provide pressure fed propulsion system concepts for consideration and to provide baseline data for potential ALS or Stand-Alone booster configurations.

Eagle Engineering, Inc. provided technical support to General Dynamics during this study. A set of specific tasks were identified to be completed by Eagle. As the study progressed the effort was re-oriented to satisfy the demands of changing groundrules. The data in this report reflects activity under the original task arrangement and the revised groundrules. Significant support was also provided to General Dynamics in development of the LRB integration plan.

Task 1 Summary Report

Task 1 of the STS Liquid Rocket Booster (LRB) study required Eagle Engineering, Inc. to supply current data relative to the Space Shuttle vehicle and systems affected by an LRB substitution.

The material transmitted consisted of selected data from NASA documents including the Space Shuttle Flight and Ground Systems Specification (JSC 07700, Vol. X), the Shuttle Operational Data Book (SD73-SH-01801i), and Interface Control Documents, as well as other NASA documents and records.

Table 1 lists those data products which were submitted individually due either to General Dynamics specific request or in compliance with the basic requirement. Much of this material was extracted from the Systems Integration Review (SIR), and Ascent Flight Systems Integration Review (AFSIG) meeting minutes and presentation material, as well as various other sources.

Table II lists those data products applicable to SRB/LRB that were part of the return to flight Design Certification Review (DCR) being conducted to certify the Shuttle System for resuming the flight program.

This task was extended to provide data products as the need arose.

Data Transmittals to GDSS
Liquid Rocket Booster Study
Table I

Item	
LRB Studies, Shuttle Constraints Summary (Huntsville)	10-14-87
JSC 07700 SRB requirements and applicability to LRB	10-30-87
JSC critical design review data relative to crew escape	11-05-87
STS-26 trajectory design data package	11-09-87
Reference mission descriptions and related configuration and performance data	11-09-87
WTR PRM-4 baseline trajectory groundrules	11-09-87
STS-51-L fluids budget, weight and C.G. data	11-09-87
LRB effect of increased length and diameter on orbiter loads	11-16-87
Action item: Booster aerodynamics and flight to wind tunnel comparison	11-16-87
SSME POGO suppressor information	11-16-87
Eagle report 86-150 - SSME Startup Transient at WTR	11-16-87
LRB heating data and STS-26 abort planning	11-17-87
Shuttle ascent key events from STS 61C	11-19-87
Design issues - review comments	11-19-87
SSME ignition timing and propellant usage data	11-20-87
Ascent abort gaps from STS 5, 6, & 9	11-23-87
LRB heating data	11-23-77
Abort boundaries STS 4 & 5	11-25-87
Intact abort windows	11-25-87
NSTS aerodynamics co-efficients (Hard copy and floppy disk)	11-25-87

Table I (Cont.)

LRB Constraints Data Book	11-30-87
SRB/Shuttle/ET Longitudinal Aerodynamics	12-01-87
Hold down post deflections	12-14-87
DCR material (see separate list)	01-08-88
Orbiter/ET ICD, STS ICD-2-12001	01-13-88
SRB/ET ICD, STS ICD-2-24001	01-13-88
Relative Impact of LRB Candidates on Flight Control	02-25-88

Design Certification Review Transmittals
Liquid Rocket Booster Study
Table II

STS 84-0575	Space Shuttle IVBC-3 Aerodynamic Heating Data Book, SRB-Ascent, May 24, 1984.
STS 84-0;259	IVBC-3: SRB Plume Heating Data Book, October 1984.
STS 82-0570	Space Shuttle System, SRB Separation Verification for Operations, November 1982.
SD 74-SH-0144E	Space Shuttle Program Thermal Interfaces Design Data Book IVBC-3, preliminary copy, September 1987.
SD 73-SH-0178	Space Shuttle Flight Systems Performance Data Book, Volume 1 C - ascent, SDM Baseline, December 1975.
STS 84-0044	Integrated Vehicle Baseline Characterization (IVBC-3), Ascent GN&C Summary Report, Volume 1: Basic & Appendixes A through D; and Volume 2: Appendixes E & F, April 1984.

Transmittal of IVBC-3 Roll Maneuver Limit Loads for Steel Case SRB's.

IVBC-3 and FWC (Filament Wound Case), Cycle 3, Orbiter High Q Loads, Revision D.

Transmittal of Revised IVBC-3 and Filament Wound Case (FWC), Cycle 3, External Tank and Solid Rocket Booster High Q Loads Documentation, Revision A.

Additional IVBC-3 Solid Rocket Booster High Q Loads.

Update to the Overpressure Data Book, STS 83-0540, containing:

1) 87-100 SRB IOP Environment for Pc (Max) Specification Requirements (Feb. 16, 1987),

2) 87-409 Methodology for Incorporating Pc Max. Change in SRB Ignition Overpressure Environment (March 27, 1987).

Transmittal of Aerodynamic Data Updates to the Aerodynamics Data Book, SD72-SH-0060-2L.

Transmittal of Shuttle Liftoff Loads for VAFB Launches with Cycle 3 Filament Wound Case Boosters (EMS 280-205-354).

Nominal Position and Maximum Excursions in X,Y, and Z Axes for Design of a Ground Umbilical/Bottom of SRB Skirt Interface.

Additional IVBC-3 High Q Orbiter/ET Attach Load Conditions for Orbiter Assessment.

Table II (Cont.)

SRB Time Consistent Liftoff Loads for Design Certification Review.

IVBC-3 Post High Q Loads.

Shuttle Liftoff Loads for Design Certification Review.

NSTS Liquid Rocket Booster

General Dynamics Corporation

Task II

Preliminary Vehicle and Facilities Impacts Assessments and Parametric Data Generation Summary Report

Prepared By

Eagle Engineering Incorporated

Preliminary Vehicle and Facilities Impacts Assessments and Parametric Data Generation

1.0 Introduction

2.0 Purpose

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4.0 LRB Impact to NSTS Ground and Flight Systems and Operations

4.1 Aerothermodynamic Evaluation of LRB Configuration

4.2 Flight Operations Evaluation of LRB Configurations

4.3 Integrated Structural Loads and Dynamics Evaluation of LRB Configurations

4.4 Main Propulsion System Evaluation of LRB Configurations

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4.6 Integrated Avionics Evaluation of LRB Configurations

4.7 Integrated Guidance, Navigation and Control Systems Evaluation of LRB Configurations

4.8 LRB Cost Impacts

Preliminary Vehicle and Facilities Impacts Assessments and Parametric Data Generation

1.0 Introduction

The primary emphasis of the Liquid Rocket Booster (LRB) study has been to define an alternate boost stage launch system for the Space Shuttle with enhanced safety, reliability, and performance characteristics. Additionally, the LRB must be integratable with Space Shuttle ground and flight systems with minimum impact. The purpose of this task (Task II) therefore is to evaluate and compare shuttle impacts of candidate LRB configuration in concert with overall trades of analysis activity.

The initial plan included Shuttle assessments of all proposed configurations and was planned to be completed within three months. The effort was delayed due to configuration definition and the down-selection process occurring simultaneously. The activity was redefined for the second half of the study to concentrate on three selected configurations with emphasis on flight loads, separation dynamics, and cost comparison. This report covers only the first half activity.

2.0 Purpose

The purpose of this report is to provide the status of Task II through March 31, 1988. Tasks to define the impacts of ascent flight loads, booster separation, and costs are in process and will be included in the final report. The five configurations being assessed, (See Figure 1) are as follows:

Configuration	Propellant	Engine	Principle Features
1B	LO2/RP-1	Pressure-Fed	Closest to SRB Geometric parameters
5A	LO2/LH2	Pump-Fed	Same propellant as current SSME's
5D	LO2/RP-1	Pump-Fed	
5J	LO@/LH2	NSTS SSME	
5K	LO2/RP-1	Saturn F-1	

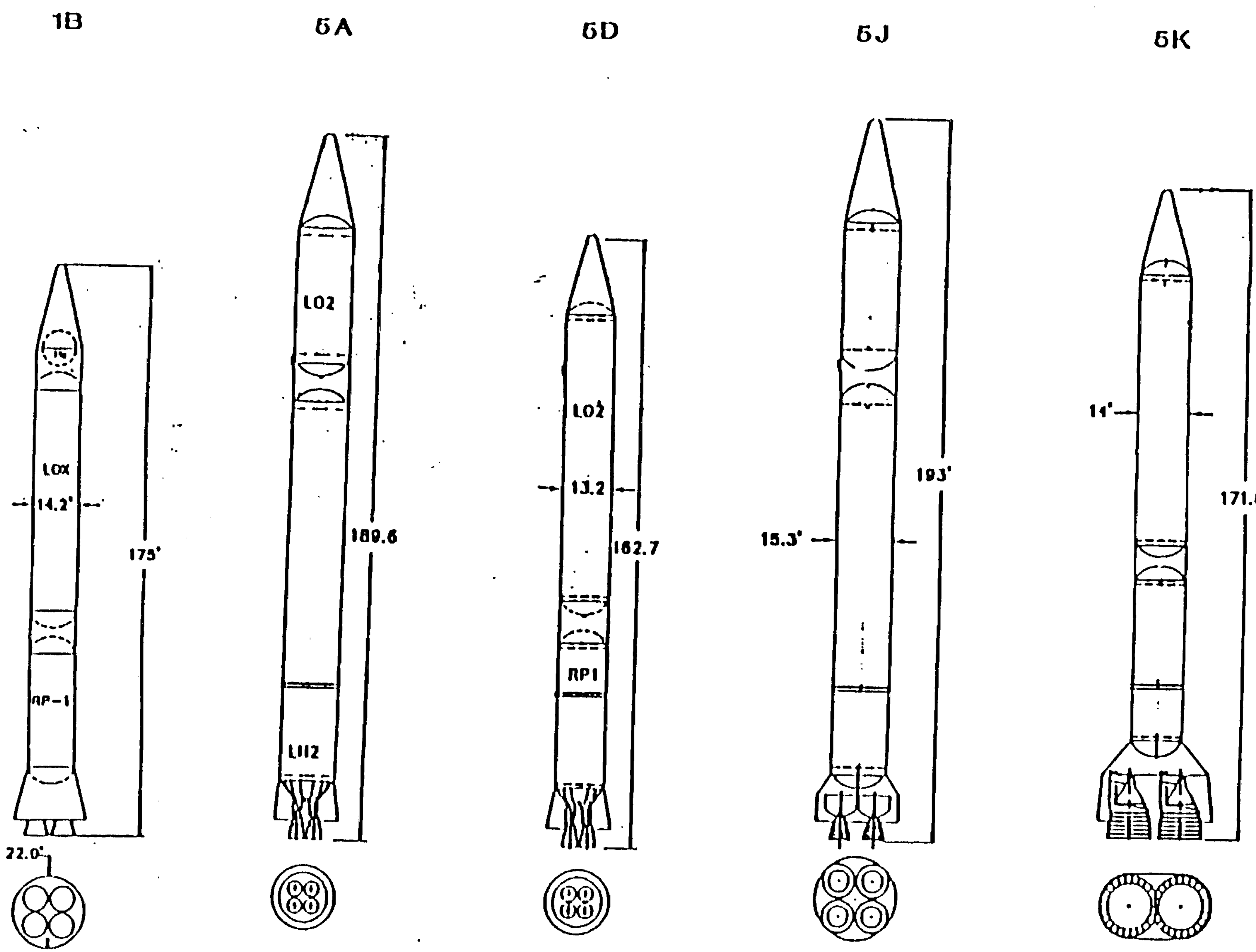
3.0 Summary of LRB Groundrules, Constraints and Design Factors

The primary groundrules utilized in assessing the impact of the LRB designs on the NSTS vehicle, facilities, and operations are:

(1) Provide capability to launch 70000 pounds to 150 nm orbit.

(2) Provide safe abort capability with one LRB or SSME engine out with a goal to be capable of abort to 105 nm orbit with one engine out.

LRB CONFIGURATIONS



Fi e 1

(3) Use existing NSTS constraints for maximum aerodynamic pressure, maximum gravity forces; day-of-launch winds; launch probability; systems dispersions; flight performance reserves; Orbiter and External Tank structural design, etc.

(4) No redesign of the Orbiter and ET thermal protection system (TPS).

(5) No redesign of the ET interface attachments.

(6) Minimum impact to Shuttle avionics and software design.

(7) Minimal changes to KSC facilities and GSE.

(8) Retain current Shuttle vehicle stability and control margins.

The primary LRB factors that must be considered in assessing these impacts are:

(1) Diameter
- Proximity and moldline effects on Orbiter and ET.
- Aeroheating impact on Orbiter and ET thermal protection system (TPS).
- Utilization of existing ET interface struts and fittings.
- Modification requirements for the mobile launch platform (ML).
- Orbiter structural loads impacts including wing (aerodynamic effects).

(2) Length
- Aeroelastic effects.
- LRB/ET forward attach loads.
- Flight control system effects.
- Modification requirements for KSC facilities/GSE. (LRB processing handling, assembly, etc.)

(3) Number of Engines
- Thrust vector control (TVC) authority.
- Abort options.
- MLP flame hole modifications.
- Startup/shutdown sequence.
- Safety/Reliability.
- Integrated avionics requirements.
- Lift-off thrust-to-weight ratio.

(4) Mass Properties
- Propellant tank arrangement.
- TVC authority.
- LRB/ET interface loads.

(5) Type of Propellant
- Performance.
- Atmosphere quality.

- Water quality.
- Plants and animal life.
- Noise/acoustics level.
- Handling/loading/spills.
- Transportation.
- Ground Handling and Loading.

4.0 LRB Impact to NSTS Ground and Flight Systems and Operations

4.1 Aerothermodynamic Evaluation of LRB Configurations

The LRB configurations were assessed to determine the impact on the heating to the baseline shuttle system, primarily the Orbiter and ET thermal protection system (TPS). All LRB configurations are longer than the SRB, and were evaluated by examining the location of each LRB nose tip relative to the ET. the resultant shock impingement from the LRB nose onto the higher heating regions of the ET forebody was assessed for its impact on the baseline TPS. The longer LRB's are thought to have minimal effect on the Orbiter forebody TPS. A qualitative assessment was made of the plume effects on the base region of the Shuttle system.

Proposed changes to the Shuttle system could impact the baseline TPS design if heating rates produced by these changes exceed the existing material capabilities. Thus, examination of the ET TPS layout and comparisons of heating rates for the ET design with those predicted with the LRB's were made. The majority of the tank is covered with a spray-on-foam insulator (SOFI), which has a heating rate limit of 10 BTU/sq-ft-sec. Various thicknesses are tabulated ranging from 2.15 inches at station 371 (x/1 = 0.024) to 1.0 inch (required to protect against ice/frost on the pad) at station 570 (x/1 = 13). A Super Light Ablator (SLA), which can withstand heating rates as high as 30 BTU/sq-ft-sec, is located under the feedlines and in the forward region of the nose which experience high heating rates from the shock off of the 30/10 degree conical tip. A slightly denser spray-on-foam, NCFI, covers the ET base region.

Two assumptions were made in developing the predicted rates for the LRB's. One is that they are attached at the same ET location as the SRB, and two, that the shock impingement distance, which occurs approximately 0.055 to 0.075 ET body lengths aft of the SRB nose tip, forward movement of the shock impingement location, the baseline value of the shock on the intertank is removed. The magnitude of the protuberance effect of the attachment may be lower for the LRB's but not felt. The high heating observed on the intertank is due to the shock from the SRB compound by the presence of the ET/SRB attachment. However, the intertank region is protected only with CPR due to the massive structure being able to tolerate the high heating.

Examination of Configurations 5A, 5D, and 5K show that a small region on the ET ogive would experience heating rates that exceed the SOFI limit and would require a modification to the TPS, such as a strip of SLA. The differences of the effect of these three concepts on the ET is small, with Configuration 5K being the smallest. The least TPS impact would be from Configuration 1B. No SLA would be required but perhaps concepts 1B and 5A would not be an additional TPS impact but may require a structural change to the intertank. The largest TPS impact would be experienced with Configuration 5J. The location of the nose tip is such that the shock impinges exactly on the nose region that experiences the high heating from the ET conical tip shock impingement. The possibility of the two phases compounding the flow field effect resulted in a factor of 2 differences predicted for the LRB effect peak value. If the maximum heating rate is 40 BTU per square-foot-second then an ablator, such as MA25 could replace the SLA. If the heating rate is as high as 80 BTU per square-foot-second, this exceeds the MA25 capability of 75 and might require a major TPS modification. A change to the length would be recommended.

Only a qualitative assessment can be made of the plume environment on the base region of the shuttle pending further definition of the concepts. A detailed analysis will be required once the configurations are better defined. Visual inspection of the engine arrangements and associated vehicle configuration indicate little, if any, differences would be detected among the five concepts.

The primary factors effecting plume base heating are: number of engines; nozzle area ratio; combustion chamber pressure; nozzle exit location; plume radiation characteristics; and vehicle base pressure. The environments are likely to be reduced for the LH2/LO2 propellants and increased for the LO2/RP-1 propellants. State-of-the-art ablators are available in the event the ET LH2 tank bulkhead requires additional thermal protection. Total vehicle base pressure must be evaluated to assure that the selected configuration does not seriously affect convective base heating environments. However, if the LRB engine plumes are located to stay within the current SRB plume boundaries at each altitude, then one could assume that the induced aerodynamic effects on the Orbiter/ET would be similar.

In summary, the thermal examination of the LRB concepts' effect on the shuttle system indicated Configuration 1B as having the least impact on the ET TPS, and Configuration 5J as having the largest. The remaining three concepts, 5A, 5D and 5K, would require a small strip of ablator material, possibly SLA, to the ET ogive in order to accommodate their thermal impact. No discriminators for the plume impact are obvious among the concepts; however, Configuration 5K appears to be the least attractive.

4.2 Flight Operations Evaluation of LRB Configurations

4.2.1 Flight Rules and Procedures

The majority of flight operations impacts involve changes to flight operations procedures. With four throttleable engines per liquid booster, there are more possible actions to consider. New flight rules and procedures must be developed to consider all options.

The flight rules and procedures changes for a liquid rocket booster system will be much more significant than a typical engine modification. New flight techniques, failure modes, and procedures for operating and managing the liquid boosters must be developed and evaluated. Updates to the launch commit criteria and the redundant set launch sequencer must be addressed.

Abort rules must be rewritten to reflect the enhanced abort capabilities made possible by liquid rocket boosters. New abort rules will be a significant part of the new flight operations procedures required.

4.2.2 Software

New flight operations software must be developed, tested, and certified to reflect the changes caused by solid rocket boosters. Software development for LRB's will be more extensive than for SRB's due to more complex valves, pumps, liquid level, slosh effects, etc., and to the increased number of engines per booster. Extensive modifications will have to be made to the software and the software must be taken through a rigorous verification process before flight. The control functions of liquid rocket boosters (e.g., valves, flows, pumps, temperatures, pressures, etc.) are more complex than those of solid rocket boosters, the orbiter pre-launch, pad switch-over and orbiter ascent phase software requirements for monitoring and controlling the LRB's will be more complex.

Another factor contributing to increased software development is the number of LRB engines. Four throttleable engines per booster adds to both the complexity and reliability of the STS system. Onboard software must be developed to prevent a thrust imbalance caused by the loss or degradation of an LRB engine.

Each of the proposed liquid rocket booster concepts all orbiter capability with loss of one LRB engine and enhances the abort capabilities with orbiter main engine degradation. New software must be developed to reflect these new flight capabilities and procedures. Software to throttle LRB engines must be developed.

The larger sizes of the liquid rocket booster concept studied will produce new aerodynamic forces and moments for which the orbiter ascent flight control software will have to compensate. New orbiter software builds, integration, test, and extensive verification will be required regardless which liquid rocket booster design is chosen. Software compensation for slosh in the new LRB tanks will have to be developed and tested.

If the liquid rocket booster has more than two controlled thrusting nozzles, then additional ascent thrust vector control drivers will have to be implemented in the orbiter avionics. This requirement in turn would impose additional complexity to the orbiter's ascent flight control software.

Studies will have to be made to see if the addition of LRB throttling capability and the possibility of different LRB thrust profiles change the area over which the external tank operates. Possible impacts of the proposed liquid rocket booster system on the Shuttle Avionics Integration Laboratory (SAIL), Shuttle simulators, Software Production Facility, System Integration Schedule D Contract, and on the STS Operations Contract (STSOC) must be evaluated.

4.2.3 Training and Simulations

Training and simulations must be updated for flight crews and flight control operators to learn in the new procedures required by the more complex control functions of liquid rocket boosters. The new abort capabilities will change the nature of abort simulations, resulting in fewer Trans-Oceanic Abort Landing (TAL) and Return to Launch Site (RTLS) simulations and more Abort Once Around (AOA) and Abort to Orbit (ATO) simulations. New malfunction procedures for liquid rocket booster leaks or hardware failure must be incorporated into the simulations. The orbiter crew must be trained to use a few new displays, monitors, and caution and warning indicators, as well as some new manual override switches. Initial hardware training costs will include updating the displays, controls, and the caution and warning lights in the orbiter mock-ups, training consoles, and in the Mission procedures.

4.2.4 Payload Integration

Payload integration will not be impacted by the substitution of liquid rocket boosters if the liftoff and ascent loads environment of the Shuttle System using liquid rocket boosters matches or is within the present envelope of the system using solid rocket boosters. The current liftoff and ascent loads environment is described in NSTS 07700, Volume 14, Attachment 1 (ICD-2-19001). If the loads are within the present envelope, the substitution will be transparent to the payload community.

4.2.5 Pre- and Post-Flight Analysis

Flight analysis will be required to assess impacts in several areas. Modifications will be required throughout the entire onboard guidance system. Ascent procedures will have to be rewritten and evaluated. The abort region determinator (ARD), which defines actual abort times based on vehicle performance, must be expanded to accommodate the increased engine number and complexity. Greater Abort to Orbit (ATO) capability will minimize Return to Launch Site (RTLS) and Trans-Oceanic Abort Landing (TAL) considerations, and may eventually simplify ascent procedures once the new software and procedures have been evaluated.

4.2.6 Real-Time Flight Control Impacts

A LRB system would require at least one new display similar to that for the Space Shuttle main engines. The substitution of more complex and versatile liquid rocket boosters will require the addition of one new backroom booster console, specializing in the valves, flows, pumps, temperatures, pressures, and malfunction procedures of liquid rocket boosters during pre-launch, launch and ascent phases.

The Booster flight control position is responsible for monitoring the main propulsion system (MPS) including the Space Shuttle main engines, external tank, and solid rocket boosters during pre-launch, launch and ascent phases.

In switching to any of the proposed liquid booster systems, the complexity of the Booster console operator's work will depend on the number of possible actions, and on the amount covered by software. Also, the orbiter crew needs the capability to manually shut down the LRB engines.

Real-time data transmitted to the ground about the liquid rocket boosters might require a separate transmitter, located on a booster. In this case, electromagnetic interference concerns must be checked pre-flight. However, this small increased downlist data requirement during ascent would have very little impact on flight control communications.

4.3 Integrated Structural Loads and Dynamics Evaluation of LRB Configurations

4.3.1 Plume Ignition Overpressure

The primary factors effecting plume ignition overpressure on the Orbiter base heat shield are: number of engines; thrust buildup rate; and engine ignition sequence. The orbiter heat shield structural limit is approximately 1.3 psi. The overpressure generated by the SSME's is significantly below this limit. The overpressure generated by the SRB's exceed the 1.3 psi limit, thus requiring overpressure control capability designed into the ground launch facilities. Although the overpressure generated by the LRB's must be evaluated, there are several factors that influence the magnitude of the LRB ignition overpressure which may negate the requirement for overpressure control. These are the slower thrust buildup rate, lower thrust level engines, and the engine ignition sequence.

4.3.2 Acoustic Environment Effects

The acoustic environment generated by the LRB engines is a factor of: number of engines; nozzle area ratio; engine operating pressure; and propellant combination. Most Shuttle payloads are sensitive to acoustic environment. However, most payloads launched on the Shuttle are designed to be compatible with the current Shuttle acoustic environment. Some Shuttle hardware also has upper operating limits. Both the Orbiter SSME's and SRB's are major sources of high acoustics, thus the combined effects must be considered. Currently, MLP high flow capacity water spray systems control acoustic levels prior to lift-off.

Such a system will be required for the LRB; however, this does not appear to be a problem for any of the configurations assessed. The current Shuttle experiences maximum acoustics after lift-off at an altitude of approximately 80 feet. Test and analyses will be required to assure acceptable environments exist or if corrective measures must be implemented. Meeting current interface limits with payloads will be a prime consideration.

4.3.3 Vehicle Dynamics Analysis/POGO Control

The current Shuttle has a POGO suppression system. The dynamic response with the LRB will require additional analyses/testing. Changes to the current POGO system are anticipated since active suppression will probably be a requirement for the LRB.

4.3.4 Engine Start Sequence/Stagger Time

The start sequence/stagger start time for the total Shuttle will have to be assessed for vehicle/facility optimization.

4.3.5 Dynamics of LRB Separation from Shuttle

Thrust from the LRB's can be terminated or reduced, thus permitting separation from the Orbiter at different times during flight, which was not the case with the SRB's. It will be necessary to develop analysis and test data relating to separation characteristics of the LRB as a function of generally different ascent scenarios including intact and contingency abort modes. This will be one of the major system areas that will require full recertification/reverification through test and analyses.

4.3.6 Effect of LRB Length and Diameter on Structural Loads

The primary concern with changing the booster mold lines from the current SRB configuration is the effect of aerodynamic loading on the Orbiter wing and Orbiter/ET attach fittings and struts during flight through the maximum dynamic pressure regime. The results of tests conducted by MSFC indicate that there is a significant effect on the Orbiter aerodynamics due to LRB diameter. The diameter should be limited to 15 feet unless additional wind tunnel data is obtained. Other observations are:

(1) Strakes should not be used as a method to permit LRB diameters greater than 15 feet unless additional wind tunnel data is obtained.

(2) Increasing the Orbiter incidence angle is not recommended due to increased payload bay door structural loads at negative angle-of-attack.

4.3.7 Load Factor

Due to potentially higher load factors with LRB's during first stage, the effect on ET tank pressure loads and structural loads may require additional ascent flight constraints.

4.3.8 Pre-Launch and Lift-off Environment

The current NSTS configuration using SRB's is very sensitive to the ignition sequence. During pre-launch operations the SSME start causes large excursions in the bending moment at the base of the stack which is resisted at the hold-down posts. At SRB ignition and release the stack responds to the residual moment in a manner called "twang". The twang response couples with the rapid SRB thrust buildup response and the SRB ignition overpressure. The current ignition sequence is designed to provide acceptable pre-launch loads and vehicle excursions without increasing the lift-off loads.

The LRB-equipped Shuttle should provide a reduced thrust build-up and overpressure environment, but is expected to have lower stiffness, and a higher excursion envelope. A combination of MLP redesign and revised ignition sequence may offset the excursions, but additional provisions may also be required.

The lower bending frequency expected will also require significant control stability analyses for slosh damping and other concerns during the early flight phase.

4.4 Main Propulsion System Evaluation of LRB Configuration

4.4.1 LH2/LO2 Configuration - Engine H2 Lag at Shutdown

Unburned H2 exits the SSME after the LO2 main valve has bee closed at engine shutdown. Some of the H2 is unburned, creating an explosion potential. A new engine for the LRB

LH2/LO2 configuration will probably have similar characteristics. The H2 quantity for the SSME's can be more than 150 pounds per engine. This problem is currently being assessed for the SSME's, and may be applicable to the LRB. Potential testing and analyses may be required to resolve this issue for the LRB.

4.4.2 LH2/LO2 Configuration - Pre-ignition H2 Purge

The SSME start sequence utilized a short H2 lead which is dumped through the engine nozzle. Accumulation below the engine followed by ignition can cause unacceptable overpressure. A H2 burn-off system has been implemented for the SSME's to assure an explosive accumulation of H2 below the engines does not occur prior to engine ignition. A similar system will probably be required for a LRB LH2/LO2 engine.

4.4.3 MPS Abort Analyses

The LRB will result in a number of new options for Shuttle. Thermal/fluid analyses for some of the abort conditions will be required to determine abort capability for both intact abort requirements and for enhancement of contingency abort capability.

4.5 Integrated Ground Systems Evaluation of LRB Configuration

4.5.1 MLP Modifications

Engine exhaust gas from LRB nozzles will be more diffused than SRB exhaust gases. A larger hole in the MLP may be required for this gas flow to avoid direct impingement. Modifications will also be required for new pad venting and work platform requirements.

4.5.2 Exhaust Trench Modifications

More study is required to determine the degree of impact.

4.5.3 Prelaunch Operations for the Engine, Intertank, and Nose Cap Volumes

Large quantities of thermally controlled N2 must be provided anytime cold and/or explosive propellants are onboard prior to vehicle lift-off. Air (possibly warmed) must be provided to purge the engine compartment for work crews. Systems include gas storage, gas heating, duct transport system, and control/monitoring instrumentation. Engine controllers, and other computers and electronic/electrical equipment generally have both low/high thermal limits, thus creating a potentially unacceptable explosive environment. The LRB configurations having no H2 have less of a thermal problem, thus require less heat. The explosive potential and monitoring requirements are less with RP propellants than with H2. The intertank and nose cap areas are of less concern as they are smaller volumes, and have less equipment and leak sources.

4.5.4 Prelaunch Environment

The probability of ice/frost formations on the LRB is similar to the ET. Thus the current Shuttle ice/debris requirements for the ET will also apply to the LRB, potentially impacting LRB TPS designs. Uninsulated RP tanks have large circumferential temperature distribution, possibly effecting structural response/design, plus non-uniform propellant heating with the potential for inverse propellant thermal stratification. However, this does not appear to be a significant LRB design problem.

4.5.5 Propellant Storage and Handling

A comparison of LH2 and RP propellant storage and handling characteristics at KSC is not completed. However, there appears to be very little difference in activating either. The primary advantages of RP propellants over LH2 are that no burn pond or vacuum jacketed lines are required, and is generally less complex to handle. Also, RP propellants can be loaded prior to flight day and require no helium tank purge.

4.5.6 Ground/Vehicle System for Propellant Tank Pressurization Prior to Engine Start

The Shuttle vehicle LH2, LH2, and RP propellant tanks for a pressure-fed LRB configuration will require pressurization prior to engine start. This will probably be accomplished with helium or nitrogen. The current ground helium system for supplying the Orbiter will probably be inadequate to meet LRB requirements. An interface with the onboard and ground for this system will be a new requirement since this interface does not exist for the current configuration.

4.5.7 MLP Holddown Release Mechanism

The holddown release mechanism and associated systems will have to be modified to incorporate new LRB requirements. These are primarily modified to incorporate new LRB requirements. These are primarily associated with the requirement to delay release until the health of all of the LRB engines has been verified, and the communication of these data to the Orbiter/ground controller. Additional studies are required to determine the optimum release procedure.

4.5.8 Pneumatic Supply

The LRB will increase the requirements for pressurized helium and nitrogen for various engine seal and cavity purges; valve actuation systems; and various flight pressurant gases. The capability of the current system will probably have to be increased to meet these requirements. Also, provisions must be incorporated to provide the status of these systems to ground control during preflight and ascent operations.

4.5.9 LO2 Geysering Suppression

Gas formation in the LO2 system can result in large surges which can be highly destructive. The critical phases are:

(1) During the initial propellant loading prior to line/vehicle hardware chill and before any significant quantities of liquid are in the vehicle lines.

(2) Once a significant quantity of liquid is in the lines or lines and vehicle,

The Shuttle has defined ground handling and loading procedures that prevent geysering in the ET. This will have to be assessed for the LRB, as the problem becomes very complex during loading, preflight and flight for multi-line vehicles with independent feed lines.

4.6 Integrated Avionics Evaluation of LRB Configurations

4.6.1 MPS Operation During Flight and Shutdown

Without adequate communication between the LRB and Orbiter to maximize performance, flexibility, and safety, the LRB becomes little more than an SRB. Communications for flight control existed for the SRB; however, it becomes more complex for the LRB with more engines, engine out, and the potential for variable thrust capability. Some of the many considerations include: vehicle control; vehicle structural loading capability; variable payload weights, various abort capabilities, etc. Minimizing the impact to the Shuttle integrated avionics hardware and software in utilizing these LRB features to enhance performance and safety is a key program driver.

The DC power required by the LRB's will likely be greater than that required by the SRB's. Power for pumps and valves to route, transport, and throttle the liquid fuel and oxidizer would be expected to add to the power required for thrust vector control, rate gyros, range safety, etc. If the LRB's are retained longer during the ascent phase for improved performance, the demand for Orbiter power would be for a longer period. Dependence upon the Orbiter for DC power may be excessive.

LRB's will require a Development Flight Instrumentation (DFI) package. Flight of the DFI package during the development flights may impact the Orbiter payload bay volume; thus, the payload carrying capacity. A DFI package for LRB's may be more extensive than was the SRB DFI due to more complex valves, pumps, liquid level, slosh effects, etc. Thus, additional cables or data multiplexing schemes may be required.

If the LRB's to be substituted for the LRB's have more than two (2) controlled thrusting nozzles, then additional Ascent Thrust Vector Control (ATVC) drivers will have to be implemented in the Orbiter avionics. This requirement in turn would impose additional complexity to the Orbiter ascent flight control software. All new software will require extensive test and verification.

Substitution of LRB's with different mold lines will result in new aerodynamic forces and moments which the Orbiter ascent flight control software will have to compensate for. Thus, new Orbiter software builds, integration, test, and extensive verification will be required no matter what the LRB configuration is. Software compensation for slosh in the new LRB tanks will have to be developed, tested, etc.

Since the control functions of LRB's are more complex than SRB's, e.g., valves, flows, pumps, temperatures, pressures, etc. the Orbiter/LPS prelaunch, pad switch-over and Orbiter ascent phase software requirements for monitoring and controlling the LRB's will be more complex. Thus, it should be expected that extensive modifications will have to be made to the software and the software must be taken through a rigorous verification process.

Incorporation of Built-in Test Equipment (BITE) in a replacement LRB could result in more extensive BITE coverage due to the more complex nature of LRB's over SRB's requiring additional Orbiter and Launch Processing System (LPS) software and its verification.

4.7 Integrated GN&CS Evaluation of LRB Configurations

4.7.1 Vehicle Control During LRB Shutdown

SRB thrust mismatch during shutdown is of significant concern to vehicle control. Normal LRB operation during a similar time frame should be more favorable. For abnormal operations the situation worsens. Analysis/testing is required to develop satisfactory operational methods.

4.7.2 Requirement for TVC on the LRB

In order for the LRB to integrate into the current Shuttle configuration, TVC capability on the LRB is considered mandatory. The Orbiter design has taken advantage of weight reductions by not being burdened with any requirements for providing control muscle during boost. The fact that the SSME's are gimballed at all is due primarily to reduce loads in the Orbiter/ET attach struts. The subsequent paragraphs provide the background and justification for the current SRB requirements which can be used as a basis for establishing the TVC requirements for the selected LRB configuration.

The 5.0 degree SRB gimbal angle requirement was established from six degrees of freedom dynamics simulations, using three sigma specification value of SRB thrust mismatch at tailoff, and putting a reasonable limitation on the amount of unwanted attitude excursion that would be tolerated. Mismatch was the main driver but also considered were thrust misalignment, Orbiter engine out, winds, and a design goal of avoiding gimbal angle saturation. In the max q flight phase there is a requirement for approximately 2.0 degrees of total SRB thrust trim in the pitch plane for the sole purpose of providing the required qx bias in the mean wind condition. Adding SRB thrust misalignment, wind shear effects, avionics failure (RM) transient, and Orbiter engine failure transients (not all simultaneously) consumes practically all of the entire 5.0 degrees, with practically nothing left over for linear control. Another design goal in addition to avoiding hitting the stops due to external disturbances, was to reserve 1.0 degrees for dynamic control of propellant slosh and to respond to attitude change command from guidance.

The 5.0 degrees per second rate requirement was established originally to provide a "bare bones" capability for "dynamic loads suppression", an original Level II Program requirement. This means phase stabilized vibration and/or slosh modes. Realizing the impracticality of this design feature for higher order modes, due to prohibitive demand on the TVC and hydraulic systems, a capability limit of roughly plus or minus 0.25 degrees at 3.0 Hertz was chosen. This alone translates into the 5.0 degrees per second requirement. The 5.0 degrees per second requirement also stems from a requirement to recover from large initial conditions on attitude and/or rate error, since it can be viewed as a limit on vehicle angular acceleration rate (jerk). Limits on acceleration rate in an otherwise linear second order system, produces instability beyond some bound on initial conditions.

These and other booster TVC requirements were established through a series of meetings of the Ascent Flight Control Panel in 1973 and early 1974, resulting in the following set of requirements to be baselined:

(1) Actuator mount geometry at 45 and 135 degrees from the plane of symmetry (as opposed to 0 to 90 degrees).

(2) Square gimbal capability pattern.

(3) Design load for actuator of 130,000 pounds.

(4) 5.0 degree usable displacement in each axis simultaneously.

(5) 5.0 degrees per second simultaneously for both actuators under full load.

(6) Minimum gimbal angle acceleration capability of 2.0 radians per second at rated load.

(7) Total duty cycle of 140 degrees per motor (read single booster thrust).

These requirements were formally transmitted to the SRB Project, from Level II, on February 12, 1974.

A word of caution on vehicle configuration. Aerodynamic moment coefficients, in a body axis system of coordinates, is perhaps the most significant design driver on TVC requirements for launch vehicle, i.e., the entire stack. Ideally they should be as small as possible for pure attitude control, but in the direction of aerodynamic stability for load relief control (an Orbiter requirement). Moving the booster nose cones forward to gain volume would shift the center of pressure forward, and locating the oxidizer tank aft of the fuel tank would move the center of gravity aft. Both of these effects will tend to increase the TVC requirements and complicate the intricate interaction between flight control and structural loads.

4.8 LRB Cost Impacts Assessments

Relative cost impacts to the NSTS systems of incorporating various configurations using a variety of propellant combinations, engine packages, and geometries was completed in the first half of the study. Development of cost models and estimates of the cost impacts for flight software, test hardware, and operational spares will be completed and reported in the final report.

Operations cost estimates will also be completed using an Eagle modified version of the KSC Operations Cost Model. The model will provide estimates of a range of traffic models using variable assumptions.

NSTS Liquid Rocket Booster

General Dynamics Corporation

Task III

Guidelines and Requirements
To Minimize Space Shuttle System Impacts
Summary Report

Prepared By

Eagle Engineering Incorporated

Task III of the STS Liquid Rocket (LRB) study required Eagle Engineering, Inc. to develop design guidelines and requirements to minimize impacts to the Space Shuttle system from an LRB substitution.

Five potential liquid rocket booster configurations were assessed in this phase of the liquid rocket booster study. These configurations consist of one pump fed system using modified existing Space Shuttle Main Engines (SSMEs), one pump fed system using modified existing Saturn F-1 engines, two newly designed pump fed engine concepts using LO2/LH2 or LO2/RP-1 fuels, and one pressure fed system using LO2/RP-1. The following lists the liquid rocket booster concepts:

Configuration	Propellant	Engine
1B	LO2/RP-1	Pressure-Fed
5A	LO2/LH2	Pump-Fed
5D	LO2/RP-1	Pump-Fed
5J	LO2/LH2	NSTS SSME
5K	LO2/RP-1	Saturn F-1

The first four configurations have 4 engines per liquid rocket booster, while configuration 5K has 2 engines per LRB. Each of the liquid rocket booster concepts considered is capable of lifting a 70 Klb payload to 150 n mi orbit. 28.5 degrees inclination with orbiter SSME's limited to 100 percent PL. The boosters must also be capable of lifting a 59 Klb payload to 150 n mi orbit, 28.5 degrees inclination, with orbiter SSME's limited to 104 percent PL. Avionics and power systems were assumed to be common to all concepts.

The design guidelines and requirements to minimize impacts to the Space Shuttle system for these five liquid rocket booster configurations are as follows:

The primary design guidelines and requirements of a liquid rocket booster system reflect the first order selection criteria.

Improved safety is a prime reason for considering liquid rocket boosters as potential solid booster replacements. Liquid rocket boosters should be designed with safety enhancements, such as the capability for intact aborts with one LRB engine out at lift-off, and possible enhanced orbit capability with degradation or loss of a Space Shuttle main engine.

Improved environmental acceptability is another advantage of liquid rocket boosters over solids. Liquid rocket booster designs improve the hazardous near field acid cloud produced by solid boosters. Liquid rocket boosters also prevent the destruction of the ozone layer caused by the combustion of solids.

Other goals of the liquid rocket booster program include Space Transportation System (STS) integration with minimum impact to the STS and launch site. Liquid rocket booster concepts were developed to minimize impacts to the orbiter, external tank, launch site, and ground support equipment.

Liquid rocket booster reliability is also of prime concern. Since the control functions of liquid rocket boosters (e.g., valves, flows, pumps, temperatures, pressures, etc.) are more complex than those of solid rocket boosters, the orbiter pre-launch, pad switch-over and orbiter ascent phase software requirements for monitoring and controlling the LRBs will be more complex. The greater complexity of liquids over solids requires added attention to LRB reliability.

In addition to the basic design rules and guidelines listed above, the following areas must be considered in the development of a liquid rocket booster system:

LRB Maximum Diameter

The maximum liquid rocket booster diameter shall be constrained to prevent increases in wing loading due to aerodynamic flow distortions. The maximum allowable diameter is approximately fifteen feet. See "Liquid Rocket Boosters - Effect of Increased Length and Diameter" in the Special Reports Summaries section for more information.

Flight Load Assessments

A key consideration to potentially upgrading the National Space Transportation System (NSTS), by replacing the solid rocket boosters (SRB's) with liquid rocket boosters (LRB's), is to assure development of an LRB design that is compatible with the NSTS and its associated system design constraints. Accordingly, the effects of LRB thrust, mass property and estimated element aerodynamic characteristics on potentially critical orbiter, external tank (ET) and interface structure were assessed throughout first stage flight for each LRB concept under study. Assessments were performed using a program containing over 80 structural load indicator algorithms that were evaluated using flight simulation trajectory parameters provided by GDSS as inputs. Figure 1 presents two typical load indicators that were evaluated. The straight horizontal lines denote the indicator structural limits while the lines with the triangular symbols correspond to the same limits but with a 90% systems dispersion protection level included. The dotted line depicts the predicted load indicator Mach-history for a particular LRB conceptual design (the RP-1 pressure fed booster in this case). For comparison, the solid Mach-history trace depicts the corresponding load indicator variation that would be predicted for the NSTS using its currently baselined solid rocket booster. As indicated, the "fwd crossbeam thrust panel" indicator shows a significant structural exceedance for the LRB case over a large portion of the trajectory beyond M=2. Similarly, a near-exceedance is seen for the LRB case at M=2.5 for the "crossbeam lower chord fitting" indicator.

Our assessment of the structural load indicators generated for each of the LRB concepts studied revealed that nearly all of the observed structural exceedances were due to excessive LRB thrust in the high Mach number range and that these exceedances could be precluded by appropriate LRB throttling. A recommended LRB throttle logic was developed based on constraining the ET LOX tank aft dome head pressure indicator to its maximum allowable value of 39.2 psi (see Figure 2). This throttle logic concept also can be adapted to protect against other LRB thrust driven load indicator exceedances should further analysis show that the aft dome head pressure indicator does not always represent the most critical load indicator exceedances.

RP1 PRESS FED LRB LOAD INDICATORS	EAGLE ENGINEERING INC.	
	T. J. ZAKRZEWSKI	May 3, 1988

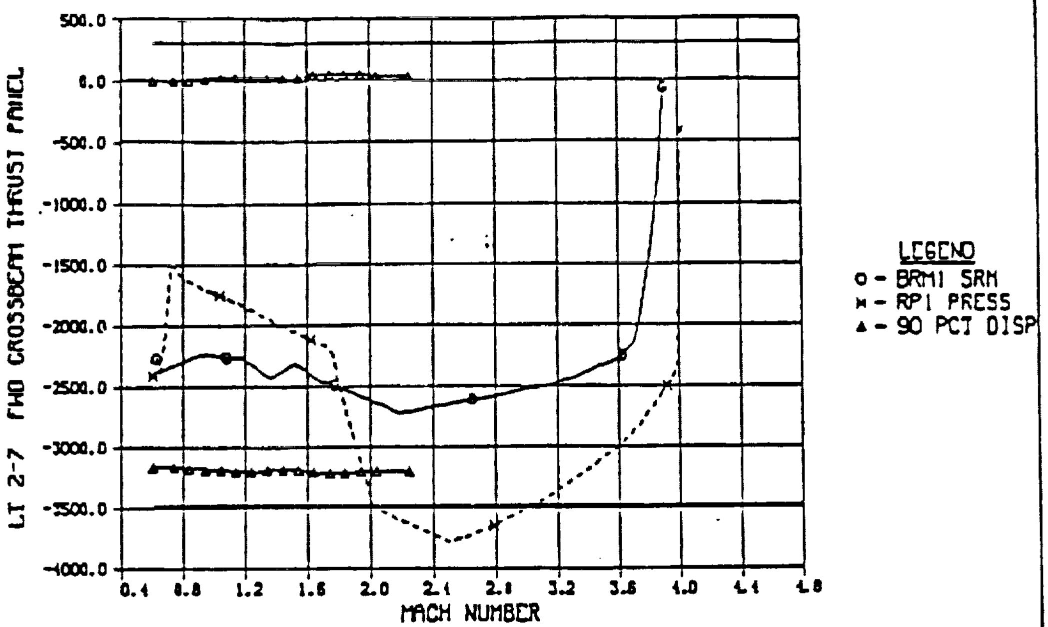


FIGURE 1 (a)

RP1 PRESS FED LRB LOAD INDICATORS	EAGLE ENGINEERING INC.	
	T. J. ZAKRZEWSKI	May 3, 1988

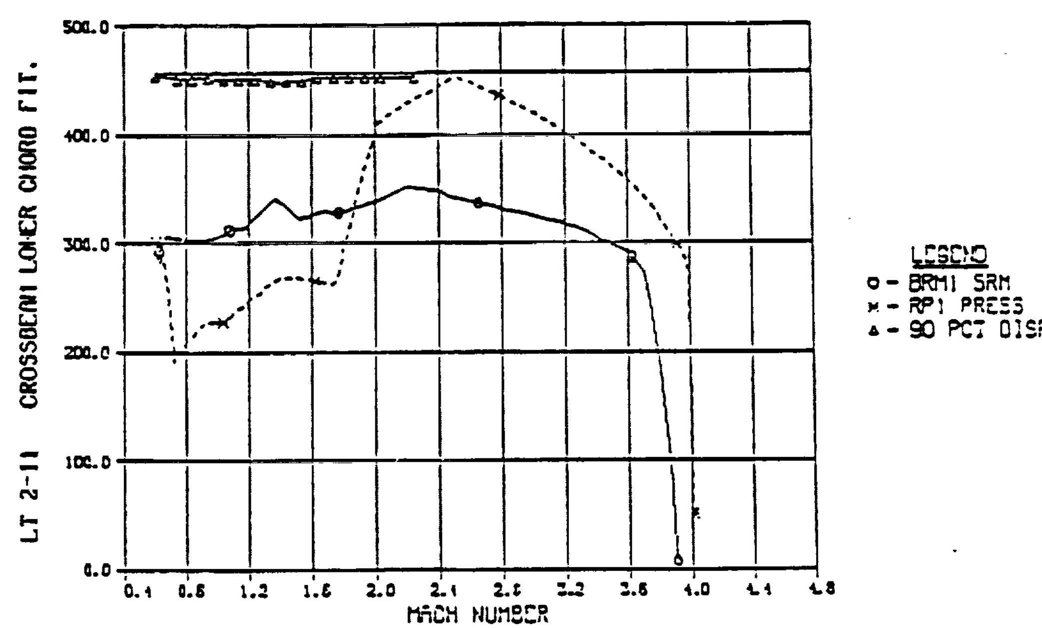


FIGURE 1 (b)

LRB THROTTLE BOUNDARY

ALLOWABLE AXIAL LOAD FACTOR VS ET LOX REMAINING

W_{LOX} – LB	$N_{X\,MAX}$
1,424,834	1.5401
1,421,860	1.6467
1,406,434	1.7690
1,372,388	1.9110
1,317,145	2.0773
1,240,555	2.2765
1,144,164	2.5172
1,030,719	2.8148
903,822	3.1722
767,655	3.6265
626,766	4.3619

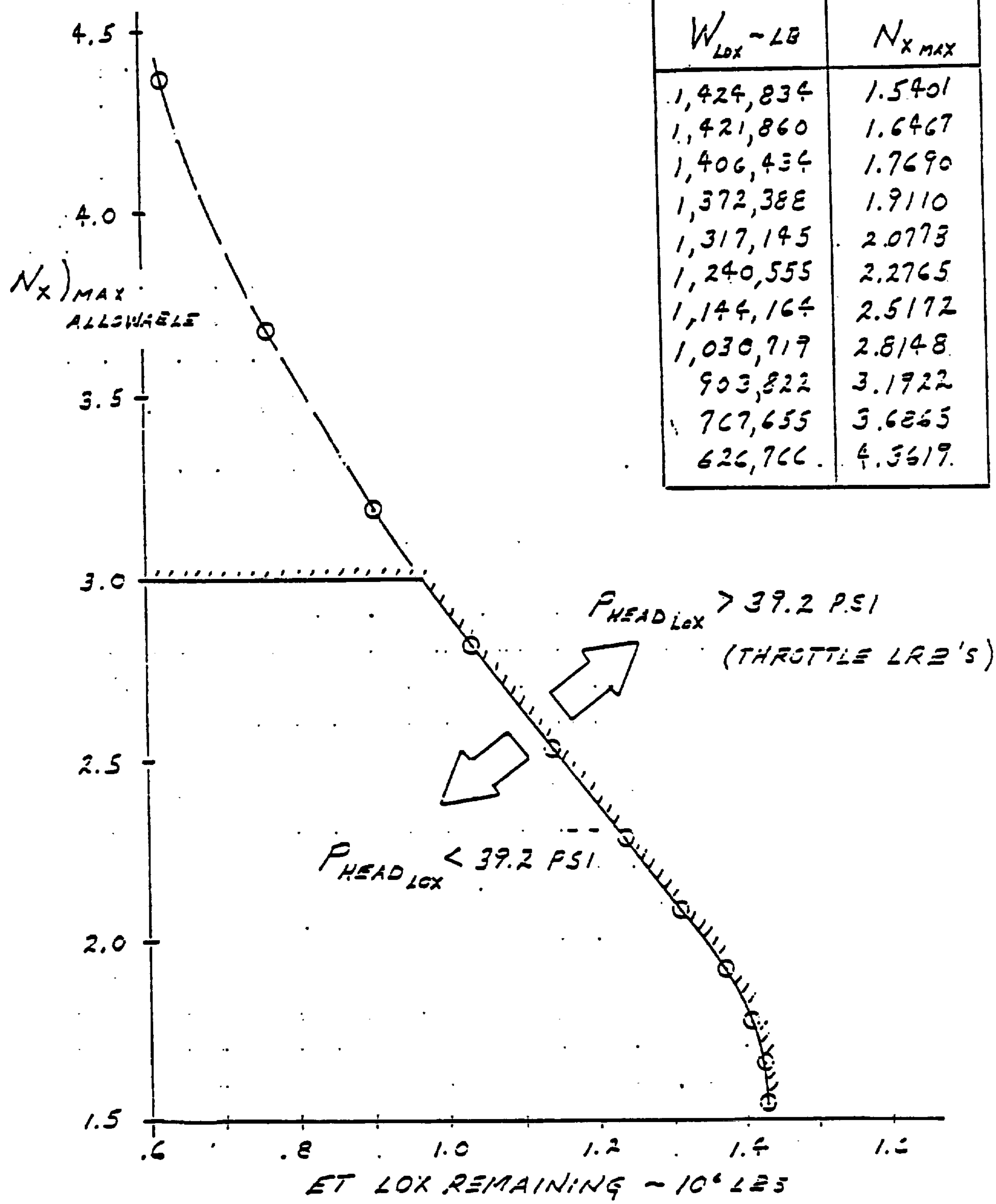


Figure 2

LRB Estimated Aero Characteristics Assessment

Reasonableness checks were performed on the estimated element aerodynamic characteristics that were used to generate the LRB structural load indicator assessments. While the vast majority of the estimated aerodynamic characteristics appeared to be quite reasonable, several anomalies were observed regarding the increments used to convert the shuttle SRB's to appropriate LRB designs. The anomalies concerned the lateral location of the LRB normal force aerodynamic center and the longitudinal location of the LRB side force aerodynamic center. Subsequently, the element aerodynamic characteristics were revised to correct the observed anomalies. However, due to programmatic priorities, updated trajectory simulations using the revised aerodynamics could not be generated, thus precluding a rigorous reassessment of the load indicators. Upon request, an estimate of the effect of correcting the LRB normal force lateral aerodynamic center was assessed (via hand calculations) relative to the aft ET/LRB interface member loads (struts P8 through P13). Results of the analysis indicated that only the lower horizontal struts, P9 and P12, would be critical and only for the LOX/H2 pump fed concept at $\pm 2.5°$ of sideslip.

Aerothermodynamics

The impacts to the baseline shuttle system, primarily the orbiter and external tank (ET) thermal protection system (TPS) were studied. The shock impingement from the LRB nose onto the higher heating regions of the ET forebody was assessed for its impact on the baseline TPS. The longer LRB's have minimal effect on the orbiter forebody thermal protection system. With the longer LRB's and the forward movement of the shock impingement location, the baseline value of the shock on the intertank is removed. The magnitude of the protuberance effect of the attachment may be lower for the LRB's. Thermal examination of the proposed liquid rocket boosters identified configuration 1b as having the least impact on the external tank thermal protection system, and Configuration 5J as having the largest. The remaining three concepts, 5A, 5D, and 5K, would require a small strip of ablator material to the external tank in order to accommodate their thermal impact.

Plume Heating

An assessment was made of the plume effects on the base region of the Shuttle system. Analysis of the plume environment of the base of the Shuttle reveals little difference among the five configurations. Plume heating is dependent on the number of engines, nozzle area ratio, combustion chamber pressure, nozzle exit location, plume radiation characteristics, and vehicle base pressure. The environments are likely to be reduced for the LO2/LH2 propellants and increased for the LO2/RP-1 propellants. Detailed plume analyses can be computed once engine specifications are defined.

Engine Throttling

All proposed liquid rocket booster configurations will have the capability to throttle the LRB engines. Individual throttling capability would significantly increase the preflight analyses, software, monitoring and controls required. Therefore it is recommended that the engines on each booster throttle as a group.

LRB Data Communications

Data communications for flight control becomes more complex for liquid rocket booster systems because of more engines, various engine out or engine degradation combinations, and possible LRB variable thrust capability. Some of the many considerations include vehicle control, vehicle structural loading capability, variable payload weights, various abort capabilities, etc. The new liquid rocket boosters must be designed to minimize both the hardware and software impacts to the Shuttle integrated avionics while incorporating these capabilities to enhance performance, flexibility, and crew and vehicle safety.

LRB TPS

The external environment surrounding the liquid rocket boosters may result in ice/frost formations similar to those on the external tank. The liquid rocket boosters should be designed in accordance with Shuttle Ice/DETSRIS requirements. This design requirement may affect proposed LRB thermal protection system (TPS) plans, possibly effecting structural response/ design plus non-uniform propellant heating with the potential for inverse propellant thermal stratification.

Acoustic Environment

The acoustic environment generated by the liquid rocket boosters must not exceed that generated by current solid rocket boosters (SRBs). This constraint addresses the sensitivities of payloads and some Shuttle hardware. Acoustic studies must consider the combined effects of Space Shuttle Main Engine and liquid rocket booster interaction.

Liquid rocket boosters will require systems to control acoustic levels prior to lift-off similar to the water spray systems presently used with the solid rocket booster system. The liquid rocket boosters must be designed to accommodate the maximum Shuttle acoustics levels which occur at approximately 80 feet altitude. In-depth tests and analyses will be required on the final configuration.

LRB Separation

The liquid rocket booster system should be designed to allow LRB shutdown and separation from the Orbiter at several times during ascent, as a function of different intact abort scenarios. The analyses and test data relating to separation characteristics of the liquid rocket boosters will define the increased safety margins of the new Shuttle system. See "LRB Separation" in the Special Report Summaries section for more information.

Hydrogen Burn-off

The Space Shuttle Main Engine (SSME) start sequence utilizes a short hydrogen lead which is dumped through the engine nozzle. Accumulation below the engine followed by ignition can cause unacceptable overpressure. This hydrogen must be burned before accumulation occurs. A burn-off system for the liquid rocket boosters is needed similar to that of currently provided for the Space Shuttle Main Engines.

SSME Hydrogen

The new liquid rocket booster design should be prepared to alleviate the problem of unburned hydrogen in the Space Shuttle Main Engines after the oxygen main valve has closed at shutdown. This issue is currently under investigation with the Shuttle using solid boosters. This issue is important since there can be more than 150 pounds of hydrogen per SSME and this unburned hydrogen creates an explosion potential. However, a solution found for the current Shuttle system and associated solid rocket boosters may also apply to a Shuttle using liquid rocket boosters.

LRB Release System

The proposed liquid rocket boosters must be designed with a hold down release mechanism and associated system to assure that all four to eight engines have started and are producing the required thrust. These facts must also be communicated to the orbiter and ground control. This is not required with the present solid rocket boosters.

LRB Purges

The liquid rocket boosters must provide for hydrogen and nitrogen purges of various engine seals and cavities, gas supply to valve actuation systems, and flight pressurant gases. These must be provided while minimizing orbiter interface and impacts.

O2 Geysering Suppression

The liquid rocket boosters shall be designed to suppress oxygen geysering in supply lines. The gas formation in the liquid oxygen system can result in large, highly destructive surges once a significant quantity of liquid is in the line or lines and vehicle. Analyses must be made of these very complex effects for loading, preflight, and flight.

LRB Thrust Mismatch

The liquid rocket booster should be designed to minimize liquid rocket booster thrust mismatch. Equal amounts of thrust should be delivered from each LRB engine for optimum ascent trajectory and to provide even thrust balances between engines during the LRB shutdown sequence. Analysis and testing will be necessary to develop satisfactory operational methods.

NSTS Liquid Rocket Booster

General Dynamics Corporation

Special Report Summaries

Prepared By

Eagle Engineering Incorporated

LRB Thermal Requirements

Examination of the heating to the Liquid Rocket Booster (LRB) configurations was made in order to determine the type of Thermal Projection System (TPS) required. The LRB heating environments were assessed relative to the Space Shuttle Solid Rocket Booster (SRB) design values and two options for TPS requirements are offered.

A estimate of aerodynamic heating was made by comparing proposed trajectories with a trajectory for which heating rates have been determined. Aerodynamic heating is a function of the square root of atmospheric density and of the velocity cubed. Thus, at the same velocity, one need only to compare altitudes (densities) to obtain the relative values.

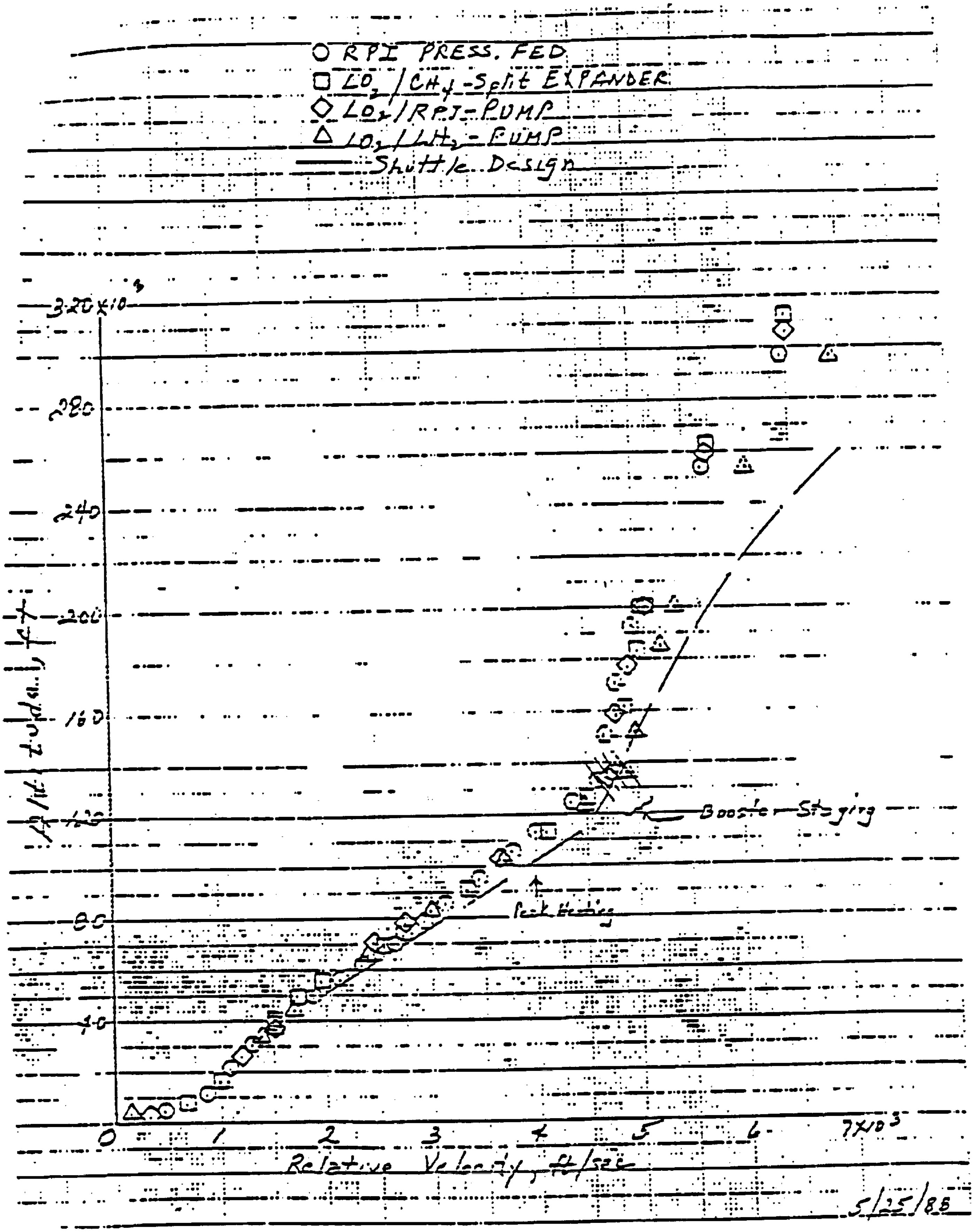
Altitude vs velocity of the proposed LRB trajectories and the aeroheating ascent design trajectory used for the Space Shuttle elements were submitted. All of the trajectories were very similar until approximately 3000 ft/sec velocity when the Shuttle design trajectory begins to deviate. At the time of peak heating, around 4000 ft/sec, the LRB trajectories are approximately 10,000 feet higher in altitude. This means the density is around 60 to 65 percent lower and the heating is 26 to 28 percent lower than the Shuttle SRB. A review of the predicted heating for the SRB revealed that a majority of the maximum heating rate values are 6.0 Btu/ft^2 sec or lower with only a few exceeding 11.0 Btu's (see LRB Thermal Requirements, Figure 1).

Insulation Requirements

Because of the Space Shuttle Program requirement to minimize ice formation on the External Tank (ET) following on-pad propellant loading to avoid ice impact on the Orbiter, a spray-on foam insulation (SOFI) is baselined for the ET. It was found that approximately 1.0 inch thickness of SOFI satisfies the minimum ice requirement. This particular insulation material, identified as CPR-488, has a maximum heating rate capability of 10 to 11 Btu/ft^2 sec and is used as an effective TPS for ascent heating.

In light of the trajectory comparisons, it is recommended that 1.0 inch of SOFI will adequately protect the LRB cylindrical structure and no doubt the aluminum nose for the 2 shorter boosters which are very similar to the SRB. The 2 longer LRBs may require additional TPS on their nose tips since they extend just forward of the ET and may not be enveloped within the ET shock. Cork would suffice for this additional TPS. For those regions of the LRB near feedlines or other protuberances, a Super Light Ablator (SLA) is recommended until the design matures or ground test data become available.

Two options for LRB TPS can be consider at this time; one for protection just past staging and the other to protect the LRB for entry. In the case of a short time flight without the need to survive entry, only SOFI would be required with a little SLA near major protuberances. However, for the LRB to withstand entry heating, cork is recommended on the nose cone and over protruding bolt heads, etc. and SLA near the cowlings and lines.



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Cost Estimation

Eagle Engineering, Inc. support to General Dynamics Liquid Rocket Booster Study included the following cost estimates:

1. Estimates for the impact of mods to the Orbiter, and other STS elements
2. Independent assessment of LRB vehicle costs
3. Estimate of the LRB software development costs
4. Definition of spares program
5. Definition of test program subsystem
6. Operations cost estimates

Cost Impact of Mods to the Orbiter and Other STS Elements

Cost estimates were developed for each of nine LRB configurations depending on several parameters including the complexity of the LRB configuration and the number of engines. The method of estimating was to develop percent changes in the STS systems as a function of the LRB design and then apply these percentages to the original STS element DDT&E.

These estimates identified impacts on the Orbiter Vehicle, primarily in the Avionics systems, impacts to the Flight Software, impacts on the Systems Engineering budgets, the MSFC projects including the External Tank and the MSFC Systems budgets. The total program costs on all STS program elements except KSC were estimated due to the modifications required to substitute an LRB for the Solid Rocket Boosters.

LRB Vehicle Costs

This exercise was conducted in support of the General Dynamics cost estimating team and consisted of EEI developing an independent parametric estimate of each of several LRB configurations based on the LRB subsystem level weight statement and complexity judgments from the EEI engineering staff. The result of this was for the customer to revise certain of his estimates and to develop more rationale in some areas that lacked technical definition. The conclusion that the GDSS Cost Estimating Relationships were comparable in several areas to the EEI CERs. Another result was that the data being supplied by the Engine manufacturers was substantially lower than what the CER estimate of engine development indicated.

Estimate of LRB Software Development Costs

In support of the GDSS cost estimating team, EEI developed an estimate for the Flight Software for the LRB. This estimate was developed based on the size of the LRB computer memory, the number of lines of code required to program the memory and the cost software programming per line of code. The estimate was essentially accepted by the customer and his customer as a reasonable software estimate.

Definition of Spares Program

Another EEI task was the definition of the Spares program and the cost of the program. This task was accomplished by estimating the initial spares requirement the initial spares laying-by reviewing the assumptions regarding vehicle checkout, production rates and availability. Based on these assumptions, and the EEI knowledge of the vehicle assembly and launch sequence, an initial spares requirement was developed which would allow the program to proceed without any delays due to availability of spares. However, not expending large sums of money for components that either would not be spared, such as structure, or would be available from the next vehicle in the production line. In addition, the EEI concept allowed for the time that the vehicle was in the VAB and on the launch pad, and certain elements would have to be replaced in a timely manner. This analysis allowed EEI to develop an initial spares requirement. The second part of this task involved estimating the operational spares requirement once the initial spares laying was established. This was again estimated assuming a "piggy back" spares concept with a probability of sufficiency (POS) of 85 to 90 percent. Once the spares requirement is established, then the cost is estimated based on subsystem and LRU costs.

Definition of Test Program

This EEI task consisted of two elements. First was the estimate by subsystem of the test hardware requirements. These estimates were developed by examining each LRB subsystem such as structure, avionics, TVC and other and making an engineering judgement of what tests were required for those individual subsystems. After developing the test requirements for subsystem development, qualification and certification, EEI converted these into equivalent subsystems and then a cost estimate was developed based on the cost of the individual subsystem. Second, the integrated test program requirements were developed based on developing analogies between the LRB engine programs and the Space Shuttle Main Engine integrated test program conducted at NSTL. For example it was felt that an integrated test program such as the STS Main Propulsion Test Program (MPTA) would be required. This test program was not for the engines alone rather for the total integrated LRB vehicle. In addition, a series of tests were defined based on the EEI technical knowledge of the test requirements.

Operations Cost Estimates

Eagle Engineering had the task to develop the total Operations cost estimates for the LRB program including facilities cost estimates, launch cost estimates and sustaining manpower cost estimates. As part of this task, the KSC launch operations cost model was obtained from KSC personnel and modified to fit the LRB program.

First, the facility requirements were developed based on the study done by the Shuttle Processing Contractor in support of the LRB study. Using the parameters from the KSC launch operations cost model, the price of the new facilities was developed. This estimate was broken into R&D and C of F in order that the customer could differentiate between budgets.

Second, the launch operations costs were estimated, again utilizing the modified KSC launch operations model. This model uses vehicle parameters, mission models, technology and several other parameters to estimate the total launch operations costs. EEI then took this output and separated out costs that would not be chargeable to the LRB program, such as R & PM costs like utilities and security, and developed the EEI estimate of the LRB launch operations costs assuming certain variable costs per launch and certain other costs such as fixed launch operations manpower.

Third, EEI presented this analysis to GDSS showing the total launch operations cost per flight, cost per lb. of payload in orbit and total fixed and variable manpower.

Flight Control Impact of LRB Candidates

The subject comparison has been performed for the Ascent Flight Control discipline. The five configurations examined are identified below. They are:

Pump Fed

Existing Engines:	SSME	1
	F-1	2
New Engines:	LO2/LH2	3
	LO2/RP1	4
Pressure Fed	LO2/RP1	5

The statement of work requested an evaluation of changes required for each, in both the pre-launch and ascent environments. Also, supply supporting rationale, and rank in order of impact. In the Ascent Flight Control System area the major discriminators appear to be as follows:

A. Number of engines

- Number of TVC drivers required (four per actuator X 2 per engine)
- Liftoff T/W with one engine out (impacts tower clearance margins)

B. Length of Booster

- Aerodynamic stability (longer booster moves CP forward)
- Lowest bending mode frequency (longer boosters tend to imply lower frequencies, all else-equal)

C. LOX Tank forward or aft

- Aerodynamic stability
  (LOX Tank forward is a dramatic improvement)
- Stiffness
  (LOX Tank forward requires higher load bearing fuel tank skin -- stiffer)

D. Pressure fed or pump - Pressure fed requires thick tank walls -- stiffer

The above categorization of discriminators are in the obvious differences between the configurations. Notice that they all are evaluated by a different set of discriminators, these being:

A. Avionics impact (#TVC servo valve driver amplifiers)

B. Liftoff T/W with engine out

C. Degree of Aerodynamic Stability

D. Lowest First Bending mode frequency

Let us eliminate the first two from this list, since they provide absolutely no discrimination between four of the five configurations and have offsetting virtues for the remaining configuration (F-1 engines). This leaves only two major discriminators for the evaluation.

Before doing the actual evaluation, which is the latter part of the task, we address the first part, i.e. changes required for pre-launch and ascent phases. In the prelaunch phase there would be changes to the gimbal test program and its pertinent "Launch Commit Criteria". In the ascent phase there would be changes in FCS filter coefficients, loop gains, trim profiles, discreets, and guidance tables. For the most part this would entail changes of existing software parameters (all of which are not "I-Load") with very little actual software structure changes. There is an avionics hardware impact for addition of more ATVC Driver Amplifier Boxes. This impact is substantial, but it is not an important configuration discriminator.

Evaluation

Evaluation Discriminators

- Degree of Aerodynamic Stability (AS)
- First Bending Mode Frequency (BF)

Parameters

- Booster Length and Diameter
- LOX Fwd/Aft
- Pump/Pressure Feed

Procedure

1. From drawings obtain lengths of the five candidates and location of LOX tanks.
2. Using the "View from Afar" (SWAG) technique visualize changes away from the reference configuration (STS with SRB's) on mass distribution, stiffness, center of pressure, and center of gravity.
3. Rank each configuration for each discriminator, where rank 1 -- 5 implies best to worst.

Groundrules and Assumptions

1. Tank length parameter is more influential on the two discriminators than tank diameters.
2. Booster mass centers for the reference configuration are near the composite mass center.

3. Redistributing booster mass away from composite mass center will lower first bending mode frequency.

4. LOX tank forward or aft will have similar impact on BF in detailing away from the reference, for the same tank length.

5. Longer tank implies lower BF, but more so for LOX tank forward than for LOX tank aft.

6. LOX tank forward has stiffer fuel tank implying higher BF.

7. Pressure-fed configuration (#5) has thicker tank walls and hence will have highest BF.

8. For LOX tank forward a length increase moves the C.G. forward faster than the C.P., hence longer is better in this case.

9. For LOX tank aft a length increase moves the C.P. forward faster than the C.G., hence longer is worse for this case.

Discriminator Ranking

The above "Partial Derivatives" are now manipulated in Table 1 below to arrive at separate rankings for each discriminator.

Table 1 - Parameters and Sensitives

Config	Description	l (Ft)	LOX Pos	AS(Rank)	BF(Rank)	FCS(Rank)
1	SSME	193	Fwd	1	3	1
2	F-1	172	Aft	4	5	5
3	NE LO_2/LH_2	188	Fwd	2	2	2
4	NE LO_2/RP-1	163	Aft	3	4	4
5	PF LO_2/RP-1	175	Aft	5	1	3

Rationale

The discriminator rankings in Table 1 are determined via the following lines of reasoning:

Aerodynamic Stability (AS)

1. More is better

2. LOX FWD superior over LOX AFT for all other combinations of parameters

3. Configurations 1 & 3 have LOX forward

4. Assumption #8 states that longer is better implying that configuration 1 ranks first and 3 ranks second

5. Of the remaining three configurations tank length is the discriminator as per assumption #9, yielding:

Rank	Config.
3	4
4	2
5	5

First Bending Mode Frequency (BF)

1. Higher is better

2. From assumptions #5 and #7 we conclude that configuration 5 ranks first.

3. Configurations with LOX fwd (1&3) also have longer length, implying lower BF according to assumption #5. This is offset by assumption #6 (stiffer fuel tank walls) when commparing these two configurations with the remaining configurations (2 & 4).

4. Presuming the impact of assumption #6 is greater than that of assumption #5, we rank configurations 1 & 3 above 2 & 4, and use relative length as the tiebreaker, yielding.

Rank	Config.
2	3
3	1
4	4
5	2

Ascent Flight Control Impact

As would be expected ranking order does not coincide for the two discriminators. Since there is no "absolute" quantitative data the direct application of weighing factors is not deemed appropriate. However, with some subjective reasoning and weighing the order shown in the final column of Table 1, above, was chosen.

Lift-off Transient Investigation

General Dynamics' "Liquid Booster Study, Volume 1, Executive Summary" states that substantial factors work needs to be done on the lift-off release system. This investigation was indicated with the goal of combining a post step impact with a partial rank impact to see how far up the "thrust curve" an explosive release system can be delayed beyond T/W = 1 before limit load of "Booster/ET" thrust fittings are exceeded. It is a trade-off between current SRB practice if "step thrust rise slope" with no delay, compared with "much shallowed thrust rise slope" with some delay. The objective is to see if we can allow the booster engines to attain somewhere near 90% thrust level before explosive release of Shuttle from the pad. There may be some advantages in staying with the current shuttle explosive release system rather than "changing out" to a "slow release" (extended metal) system.

After some preliminary analysis, a computation was made for launch pad release at 87% full thrust level. This resulted in loads very slightly exceeding (1.2%) the design limit loads of the thrust fittings. An 86% level of thrust at release would undoubtedly result in loading with in the design limit loads of the fittings.

If the performance of the engines can be assessed by the time the engines reach the "mid-80" percent level, then explosive (sudden) release from the launch pad appears to be satisfactory.

Time ran out to develop transfer function and resulting of the "skin-stringer" design. Response was generated for the monocoque design only.

Study Description

The GD LO2/LH2 18 ft. diameter liquid booster was examined both the "monocoque" version and the "skin-stringer" version. The monocoque version was found to have the same frequency characteristics as the present SRB Shuttle configuration, i.e. 19 Hz longitudinal frequency for the pair of booster and 4 Hz longitudinal frequency for the lumped "orbiter/ET" mass. The "skin-stringer" design has frequencies of 14 Hz/3 Hz, respectively.

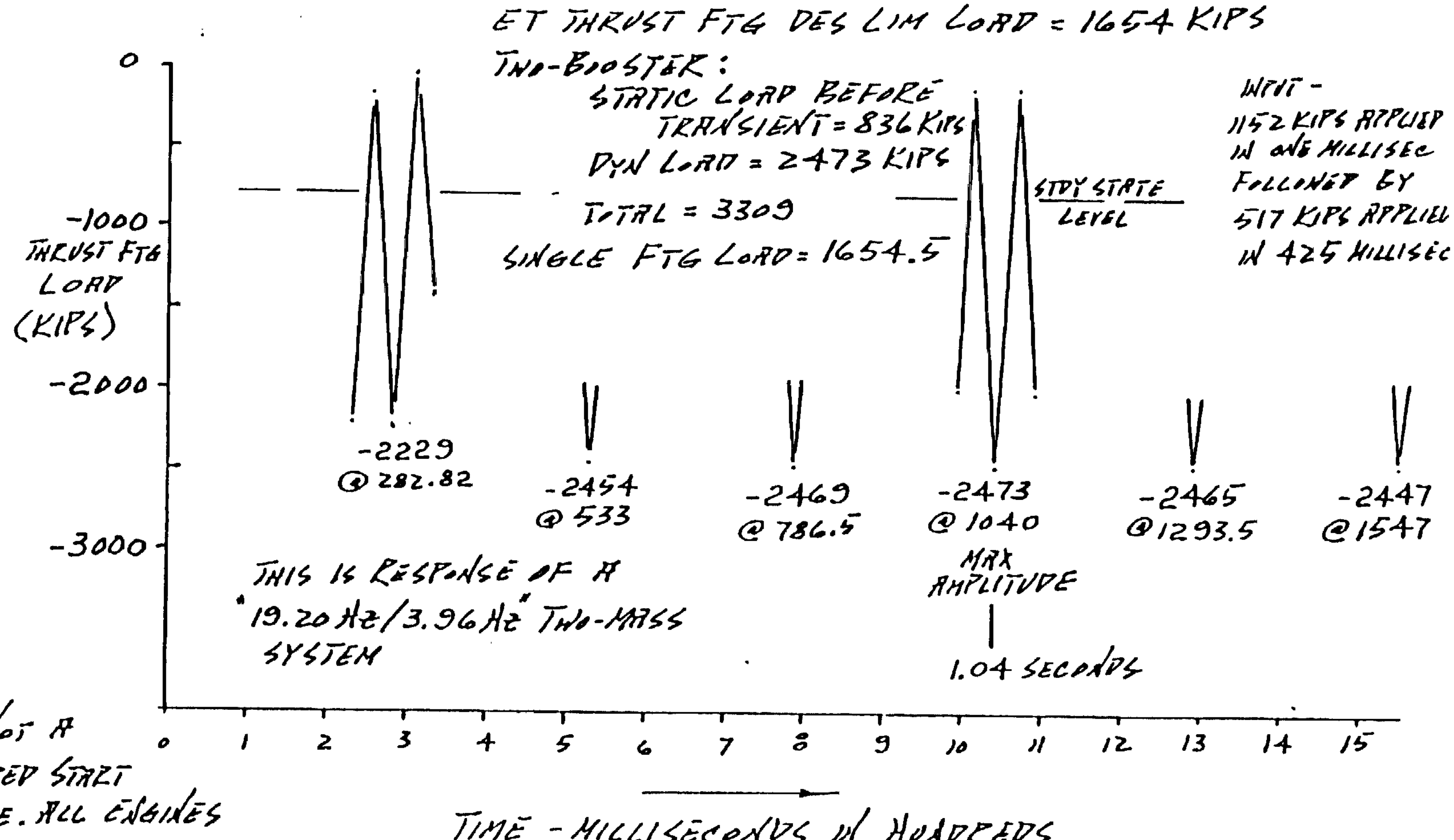
Figure 1 are the computations of weights, load levels and stiffnesses of the boosters. Figure 2 is examination of these load levels with thrust rise slope and roll over of the "helium spin" engines (page 5-12, GD Volume II final report). Examination of vehicle configuration, led to the inputs for frequency determination.

Figure 4 is the same type data for the current SRB Shuttle configuration for comparison. Since the monocoque version of the GD LRB had the same frequencies as the SRB, the SRB transfer function was used (figure 5). The response nature of this transfer function has been previously given to General Dynamics. It is shown as figure 6 here, with the magnitude points "V", "W", "X", "Y", and "Z" labeled. These are the points around the high load point "X". This plot (figure 6) is the average of the first five shuttle flights.

The five labeled points were investigated for "step" input, and are plotted on figure 7. Looking back to figure 2 and the computation on figure 7, it is seen that about 78% of thrust level is all that can be tolerated and not exceed ET thrust fitting (and back-up structure) design limit load.

GENERAL DYNAMICS LO_2/LH_2 "MONOCOQUE" PUMP-FED BOOSTERS

LIFT-OFF TRANSIENT WITH RELEASE FROM LAUNCH PAD DELAYED TO 87% FULL THRUST LEVEL



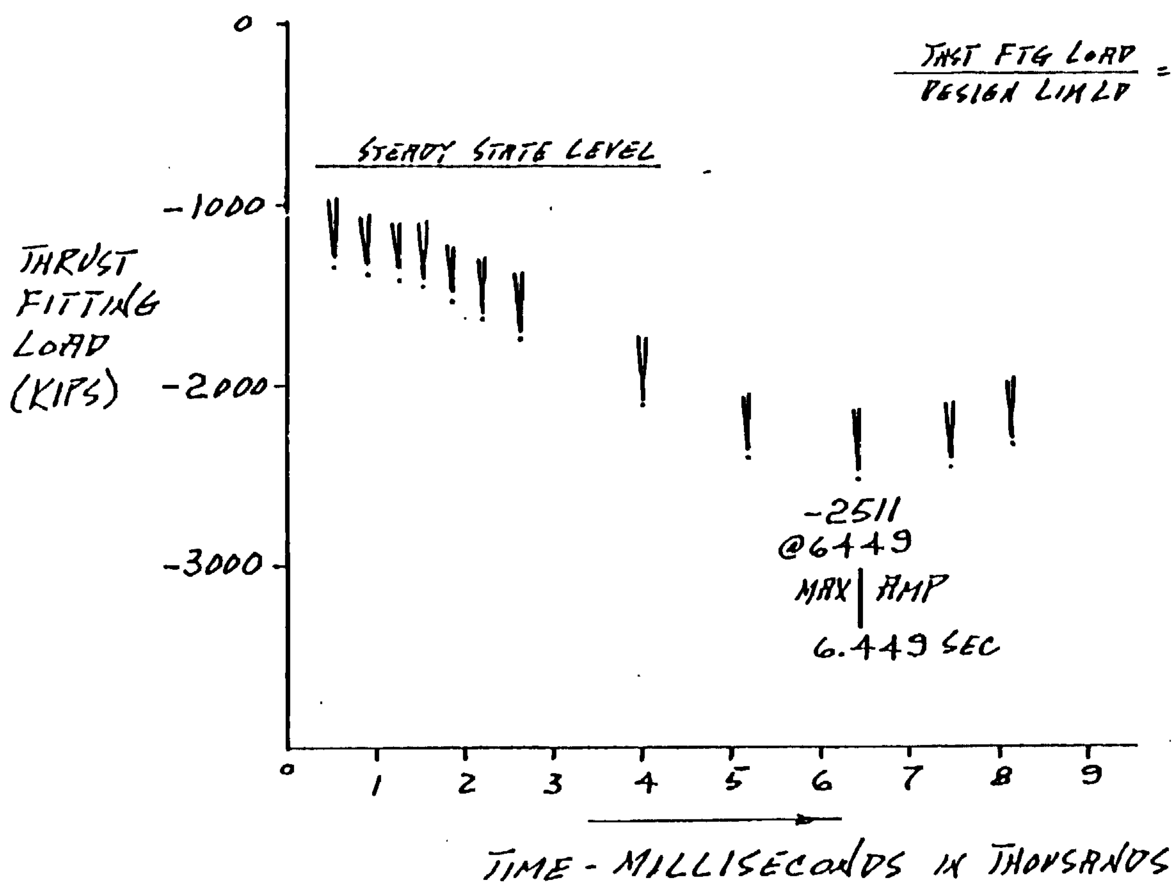
NOTE -
THIS IS NOT A STAGGERED START RESPONSE. ALL ENGINES STARTED AT SAME TIME

WILL HOYLER
12-2-88

GENERAL DYNAMICS LO_2/LH_2 "SKIN-STRINGER"
PUMP-FED BOOSTERS

LIFT-OFF TRANSIENT WITH RELEASE FROM LAUNCH
PAD DELAYED TO 87% FULL THRUST LEVEL

$$\frac{\text{THST FTG LOAD}}{\text{DESIGN LIM LD}} = \frac{2511+836}{1634 * 2} = \frac{3347}{3268} = 1.024$$



THIS IS RESPONSE OF A
"13.97Hz/2.87Hz"
TWO-MASS SYSTEM
INPUT WITH A 1152 KIP
STEP INPUT OF ONE MILLISEC
FOLLOWED BY A 517 KIP
RAMP INPUT OF 425 MILLISEC.

WILL HOYLER
12-2-88

TRANSFER FN FOR
GP LO_2/LH_2 "MONOCOQUE"
BOOSTER (19.20HZ/3.96HZ)

2.4126^{-3} $\overline{|}\,6.031858^{6}$ $\overline{|}^{2}\,\omega = 24.881414$
$\zeta = .00001$
$\alpha = -2.4881414^{-4}$ ← M_1
$\beta = 24.881414$

1.200649^{-6} $\overline{|}\,6.031858^{6}$ $\overline{|}\,1.244071^{6}$ ← M_2

$s^4 + 3.52303^{-3} s^3 + 15934.602 s^2 + 8.7358 s^1 + 9.009741^{-6}$

$\overline{|}^{2}$ $s^2 + 3.07133337^{-3} s + 15347.6 0076$

3.85602 Hz
$t = .259335$

$\omega = 24.22809866$
$\zeta = 9.32178228^{-6}$
$\alpha = -2.2584907^{-4}$
$\beta = 24.22809866$
$a = 4.51698^{-4}$
$b = 587.0007648$

$\overline{|}^{2}\,\omega = 123.885434$
$\zeta = 1.2395862^{-5}$
$\alpha = 1.535666686^{-3}$
$\beta = 123.885434$

19.716979 Hz
$t = .0507177$

$\left(\frac{.259335}{.0507177}\right) = 5.1133$

$\omega_1 = 19.20\,Hz = 120.63716\ R/S$
$\omega_2 = 3.96\,Hz = 24.881414\ R/S$
$\zeta_1 = \zeta_2 = .00001$
$\frac{m_2}{m_1} = 1944/1579 = 1.23116$

$\bar{A} = .00034$
$\bar{B} = 619.085$

WILL HOYLER
11-30-88

TRANSFER FN FOR
60 LO_2/LH_2 "SKIN-STRINGER"
BOOSTER (13.97 Hz / 2.87 Hz)

1.7553^{-3} $\overline{|}4.3888^{6}$ $\overline{|}^{2}$ $\omega = 18.03274$ ← M_1
$\zeta = .00001$
$\alpha = 1.8033^{-4}$
~~$\beta = 18.03274$~~

6.33137^{-7} $\overline{|}4.3888^{6}$ $\overline{|}9.01637^{5}$ ← M_2

$s^4 + 2.5602^{-3} s^3 + 8430.1717 s^2 + 3.3496 s + 2.505393^{6}$

$\overline{|}^{2}$ $s^2 + 2.232668^{-3} s + 8421.7378$

2.7951 Hz $\omega = 17.56229$
$\frac{1}{2} = .357766$ $\zeta = 9.32487^{-6}$
$\alpha = 1.63766^{-4}$
~~$\beta = 17.56229$~~
$a = 3.2753^{-4}$
$b = 308.4339$

$\overline{|}^{2}$ $\omega = 90.12068$ ~~467~~ 14.343
$\frac{1}{2} = .069$
~~$\zeta = 1.23871^{-5}$~~
$\alpha = 1.116334^{-2}$
$\beta = 90.12068$ ~~466~~

$\frac{.357766}{.06972} = 5.1315$

352
70

$\omega_1 = 13.97\text{ Hz} = 87.7761$ R/s
$\omega_2 = 2.87\text{ Hz} = 18.03274$ R/s
$\zeta_1 = \zeta_2 = .00001$
$\frac{M_2}{M_1} = 1944/1579 = 1.23116$

$A = 2\zeta\omega = .0003607$ .0002800
$B = -\omega^2 = -325.17971$

WILL HOYLER
11-30-88

LRB Effect on Shuttle Heating

The effects on the Space Shuttle elements of replacing the Solid Rocket Booster, SRB, with Liquid Rocket Boosters, LRB, has been investigated for the aerodynamics heating impact. The various options offered by General Dynamics Space Division were reviewed as to the effect of the different lengths of the LRB's on the ET forebody and the Orbiter base regions.

External Tank (ET) Forebody

An assessment of the heating impact was made by comparing the proposed heating with the baseline design values. Figure 1 shows a distribution of the maximum heating rates that are used for the baseline ET TPS on the ET ogive and intertank regions. (Figure 2 identifies these regions). The magnitude of the heating rates dictate the type of TPS. Because an inch of insulation material, SOFI, is required to insulate the tank from ice formation while the vehicle is on the pad, it was decided to also use the SOFI as the TPS. Characteristics of this material are such that at heating rates above 8 to 10 Btu/ft^2-sec, SOFI is assumed to have ablated off of the structure. Therefore, at higher heating rates, Super Light Ablator (SLA) is used which can withstand heating rates up to 30 Btu/ft^2-sec. Figure 3 illustrates the ET TPS.

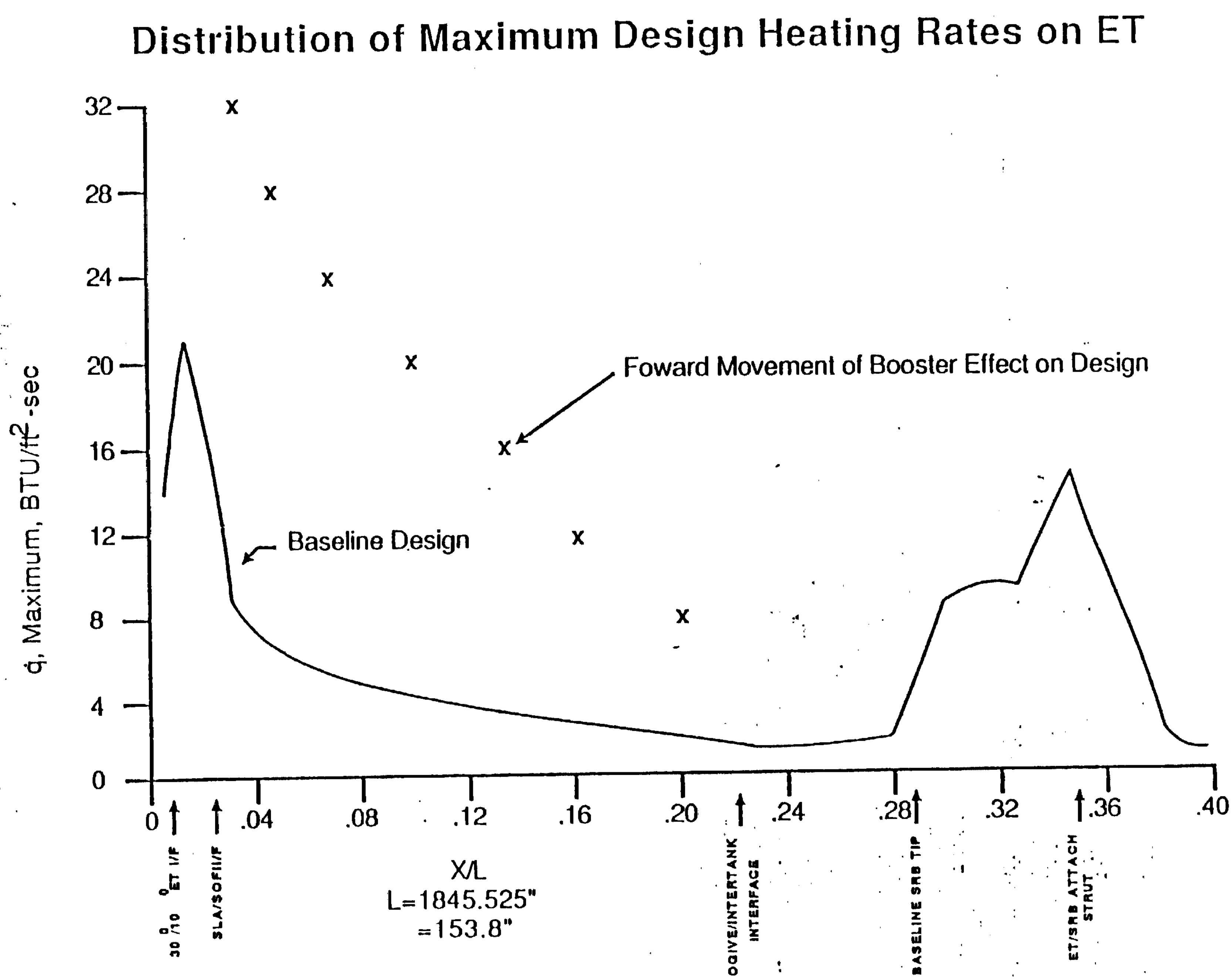
Examination of Figure 1 shows two regions of high heating on the forward ET. The heating near X/L of 0 is a result of the shock from the 30°/10° conical tip onto the ogive and the heating on the intertank is the result of two influences. The first is from the shock off of the SRB which impinges on the ET between an X/L of 0.28 to 0.30. The second is due to protuberance heating around the ET/SRB attach point at X/L of 0.357. On the intertank, the high heating can be accommodated with the massive intertank structure. Note on Figure 1 that the tip of the SRB is opposite the ET X/L of 0.225 and the shock impinges a delta distance downstream of 0.055 to 0.075 which corresponds to a distance of 8.5 to 11.5 feet. The shock impingement increases the heating by a factor of four whereas the shock off of the ET tip onto the forward ogive is a factor of approximately two. In an effort to illustrate the impact of a longer LRb whose nose is forward of the baseline SRB, the design heating values have been increased by a factor of four. In order to not exceed the allowable 30 Btu/ft^2-sec for SLA, (whose interface occurs at X/L of 0.04) the forward movement curve suggests that the LRB nose tip should not be more than 1.5 to 5.4 feet ahead of the ET. This assumes that the shock impingement is still 8.5 to 11.5 feet aft of the LRB nose tip. There are ablators with higher heating rate capability such as MA-25S which is heavier than SLA but can take heating rates up to 75 Btu/ft^2-sec.

Orbiter Base Regions

There are many variables associated with the prediction of plume radiative heating rates. Factors such as chamber pressure, nozzle exit area, type of fuel and oxidizer, turbulent exhaust afterburn and view factor are required to be known in order to determine the plume shape and the radiative environment. Using the Shuttle predictions as a calibration and consulting with several experts, it was decided that the LRB's would produce less radiation than the SRB's with some estimates as much as 50 percent less. For this study, it is recommended that 30 percent less radiation be assumed.

Examination of Option 9 with the three vertical nozzles, reveals that the LRB nozzle is approximately 5 feet closer to the Orbiter body flap trailing edge than the baseline SRB nozzle; that is, 15 feet as opposed to 20 feet, based on scaling option 9 and option 1 drawings with the simplifying assumption that radiation is a function of the distance squared, option 9 would produce approximately 56 percent higher heating than option 1. However, the resultant effect is only a 9 percent increase to the Orbiter Body flap trailing edge baseline. This is illustrated in Figure 4 which shows the predicted heating rate to the trailing edge for the baseline and for the LRB's. The curve labeled "SRB Radiation" is the current design value for the SRB radiative heating component of the total heating to the body flap. (The SSME + SRB Radiation is the total.) The bottom long-dash curve is the assumed 30 percent reduced radiative heating of the LRB plume to the trailing edge and the "option 9 LRB" curve is the 56 percent increase to the LRB radiation. Because the LRB's would lack liner material and residual solid propellant particles, they would not exhibit the high shutdown spike that the SRB's produce at separation.

The option 9 drawing suggests that the nozzles are touching each other. If they are to be gimballed and are spaced, then the upper nozzle would be nearer to the Orbiter with a resultant higher radiative heating to the trailing edge. The present maximum heating rate shown of the total SSME plus option 9 LRB is around 25 Btu/ft^2-sec. This corresponds to a radiation equilibrium temperature of 2350°F. While the current TPS on the trailing edge can take 2300°F for 100 reuses and around 2600°F for one use, it is recommended that the option 9 study be judicious in establishing its proximity to the body flap.



Distribution of Maximum Design Heating Rates on ET
q, Maximum, BTU/ft2-sec
32
28
24
20
16
12
8
4
0
Foward Movement of Booster Effect on Design
Baseline Design
0
.04
.08
.12
.16
.20
.24
.28
.32
.36
.40
30°/10° ET I/F
SLA/SOFII/F
OGIVE/INTERTANK INTERFACE
BASELINE SRB TIP
ET/SRB ATTACH STRUT
X/L
L=1845.525"
=153.8"

FIGURE 1

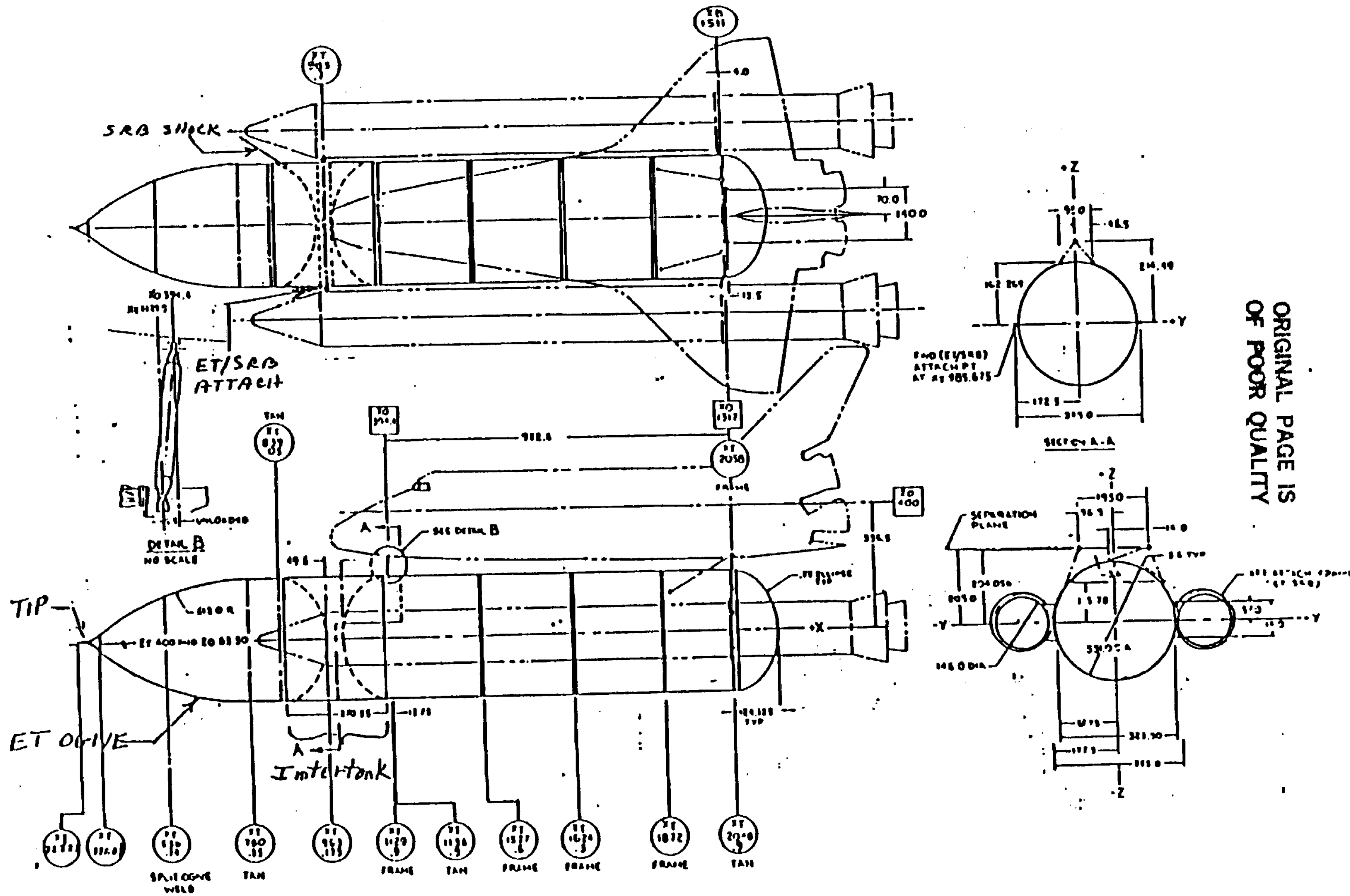


FIGURE 2 SHUTTLE SYSTEM LAUNCH CONFIGURATION

FIGURE 2

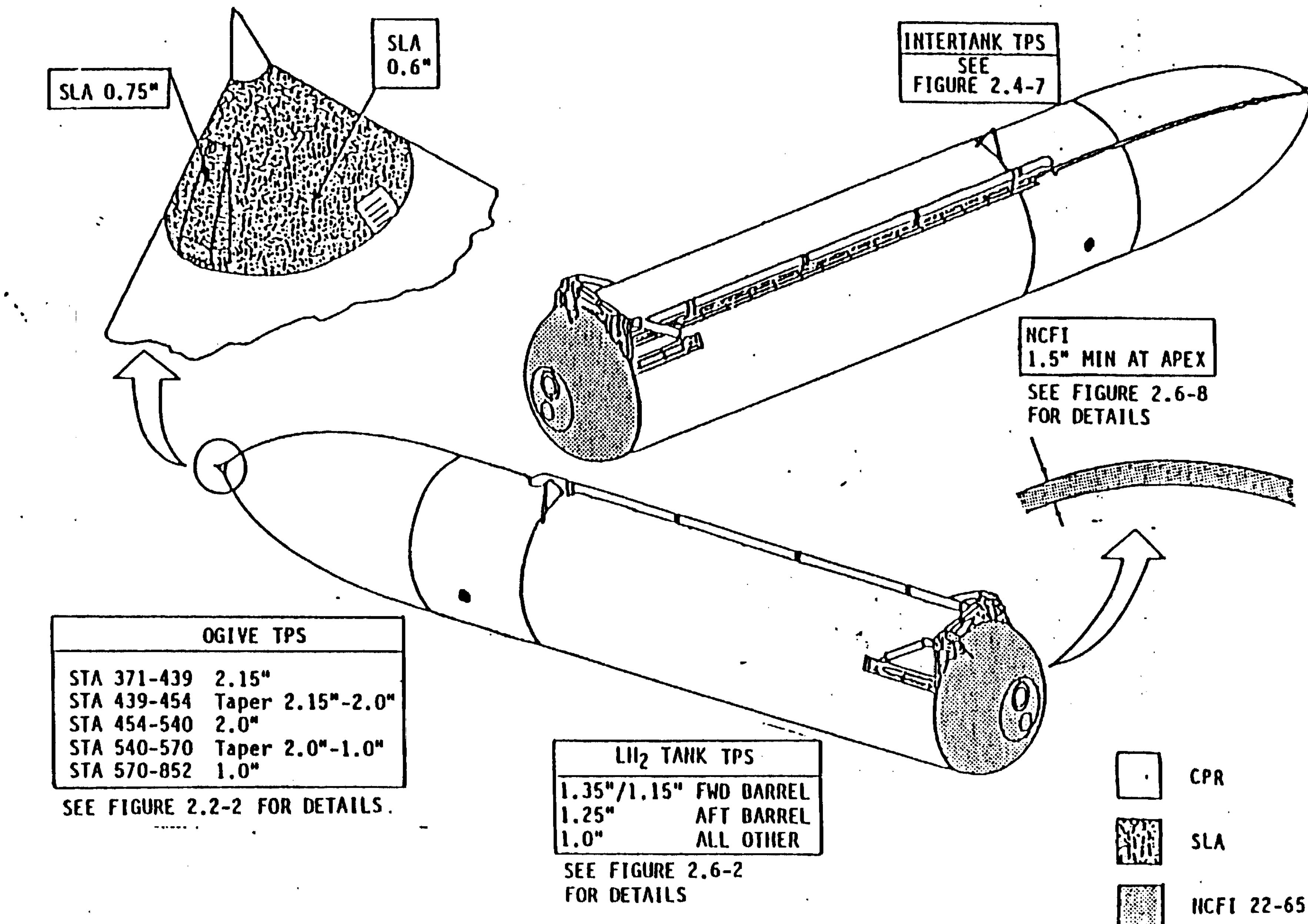


FIGURE 3.0: ET TPS CONFIGURATION OVERVIEW (LWT 44 & UP)

FIGURE 3

EAGLE

Design Plume Heating Rates to Orbiter Body Flap Trailing Edge

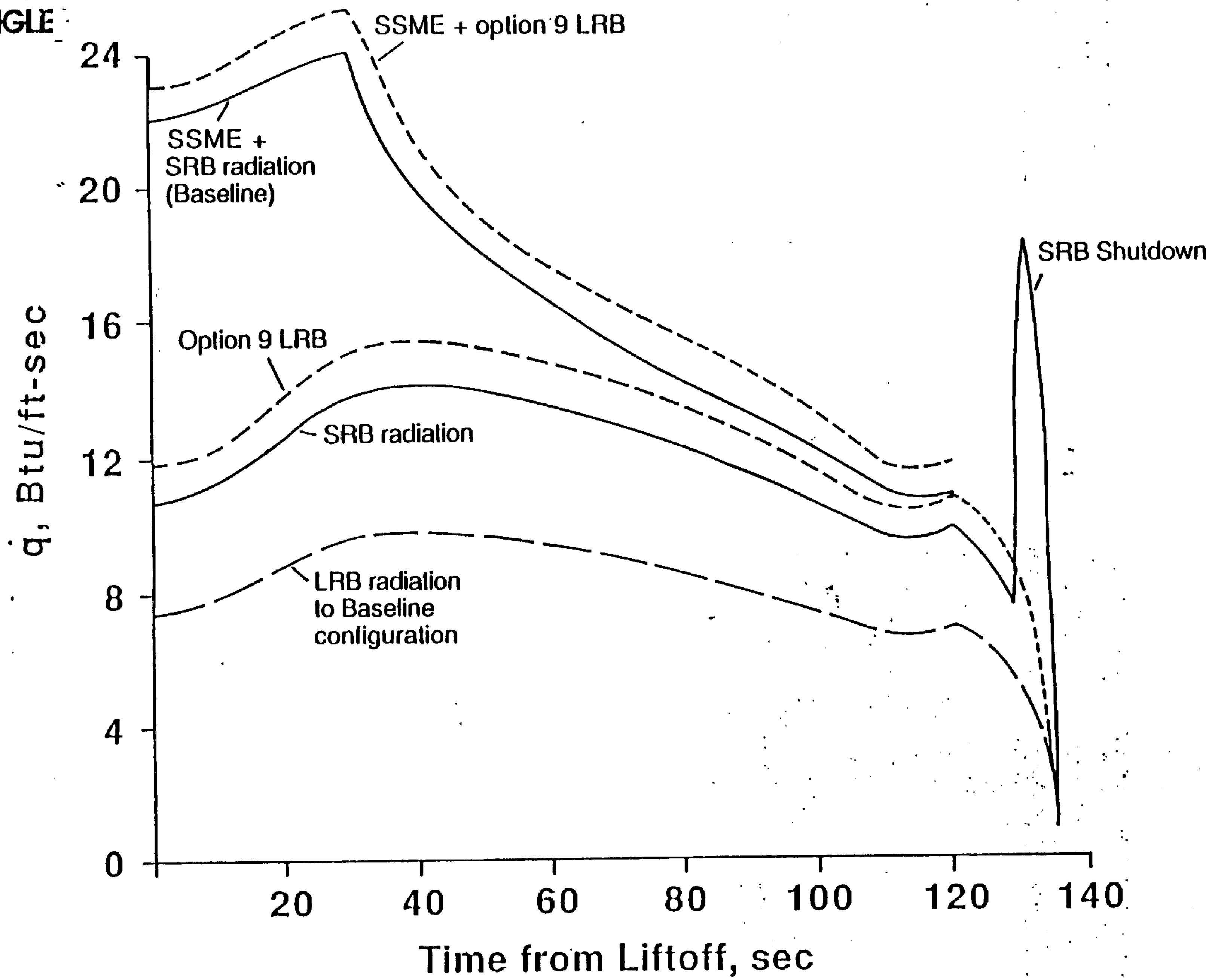


FIGURE 4

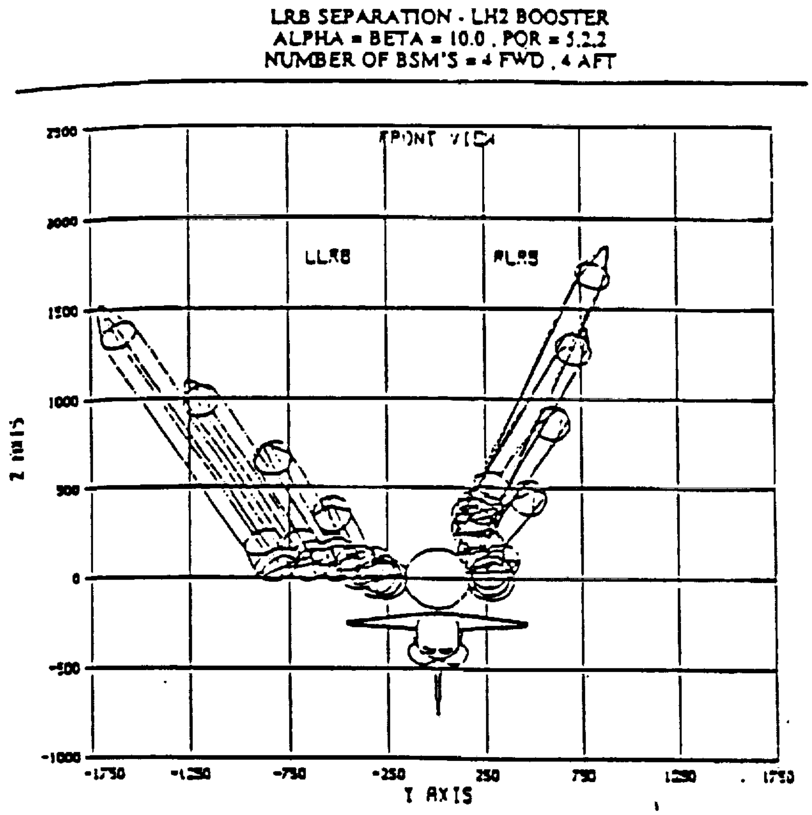
LRB Separation

A preliminary analysis of LRB Separation was performed to evaluate their impact on the separation system. The conditions that were examined consisted of nominal separation along with aborts at 100 and 75 seconds. Four LRB configurations were examined. They were LOX/LH2, LOX/RP1 pressure fed, LOX/RP1 pump fed, and LOX/CH4. In general, the nominal separation conditions did not pose a problem for any of the LRB configurations. An off-nominal case was run for all of the configurations. The conditions for this case were as follows:

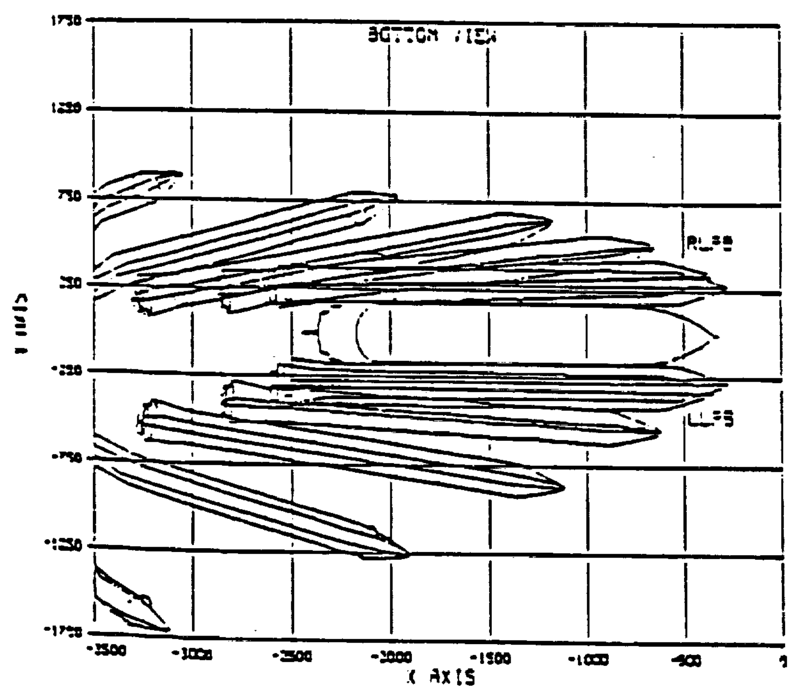
Alpha=Beta= 10 degrees, roll, pitch, yaw rate = 5,2,2 degrees/sec.

A pictorial presentation of the LOX/LH2 booster separation for the above conditions is presented in Figure xx. The LOX/RP1 pressure fed booster was the only one that had a problem with this design point. Due to the heavier weight of the pressure fed booster and the location of its center of gravity, it required additional thrust for a clean separation.

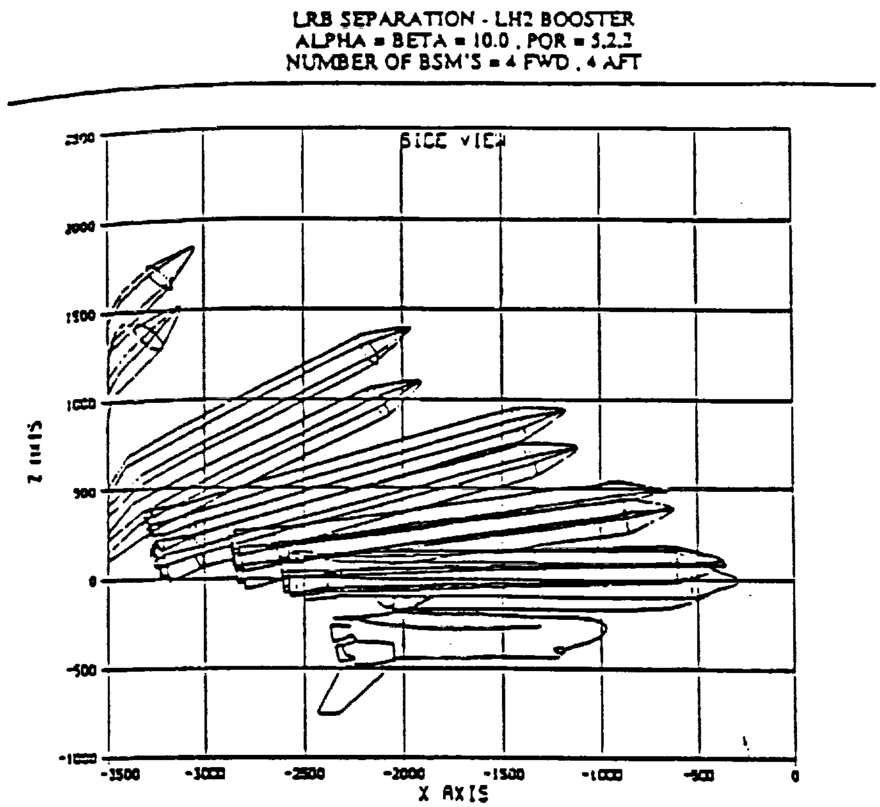
Only the LOX/LH2 configuration was studied for the abort conditions. There are several problems that affect abort separations. They are the increased weight of the vehicle, the center of gravity is farther forward, and the dynamic pressure is considerably larger than normal. These problems tend to make separation difficult for aborts. Compounding the problem is the fact that the proximity aerodynamic flowfield for the boosters is completely different from the nominal separation environment. For an abort at 100 seconds the thrust on the booster separation motors would have to be increased approximately 25 to 50%. At 75 seconds the center of gravity is so far forward that it is difficult to rotate the LRB nose away from the External Tank. It was found that the forward thrust would have to be increased by 100 to 150% to have any chance at a successful separation.



LOX/LH2 Pump-fed Nominal Ascent (Design Case) Separation, Front View



LOX/LH2 Pump-fed Nominal Ascent (Design Case) Separation, Bottom View



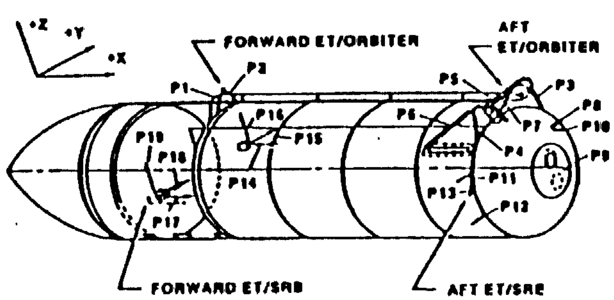
LOX/LH2 Pump-fed Nominal Ascent (Design Case) Separation, Side View

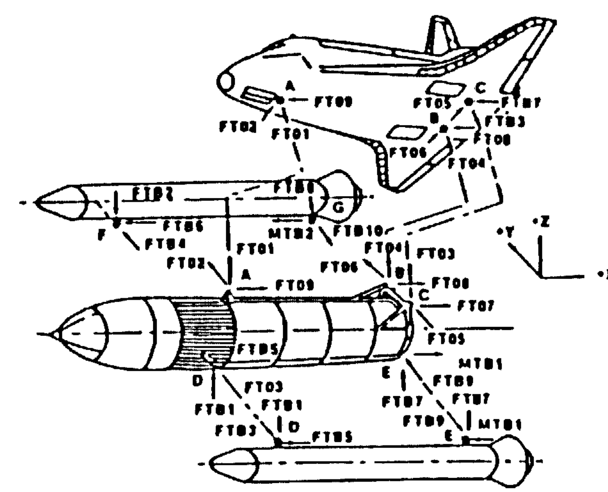
Liquid Rocket Boosters Effect of Increased Length and Diameter

Studies were made of possible Liquid Rocket Booster lengths and diameters to identify constraints which would prevent increases in wing loading due to aerodynamic flow distortions. The following charts show the findings of these studies.

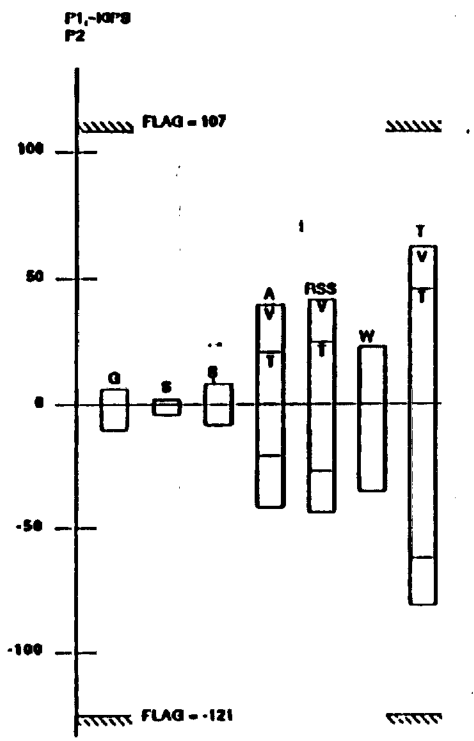
LIQUID ROCKET BOOSTERS
EFFECT OF INCREASED LENGTH & DIAMETER

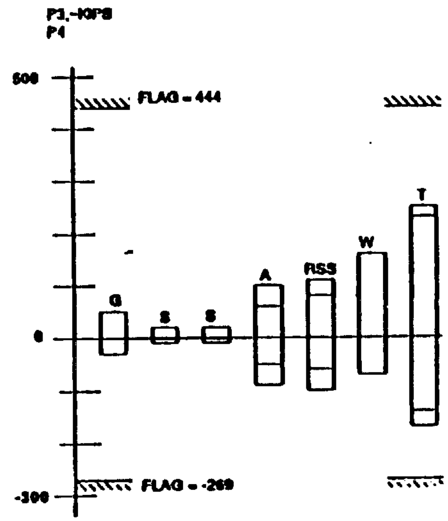
- PAST STUDIES HAVE SHOWN - THE MAJOR LOAD CONSTRAINTS IN THE MAX q REGION
  - ORBITER WING
  - FITTINGS- FT01, FT06
  - MEMBERS P_1, P_2, P_3, P_4, P_5, P_6, P_7

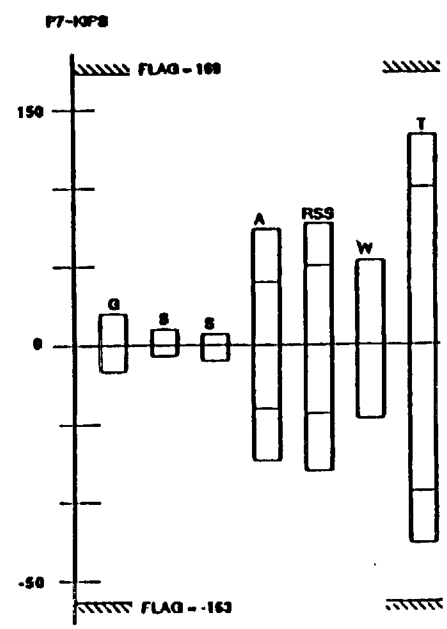


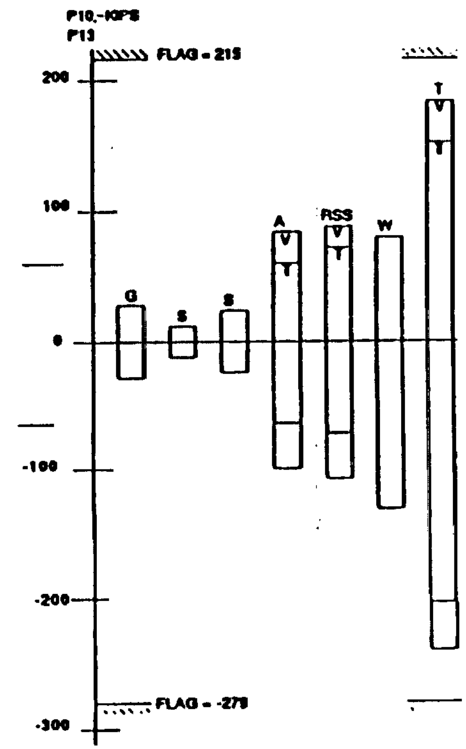


EFFECT OF AERODYNAMICS ON MAX q - LOAD CONSTRAINTS - MEMBERS



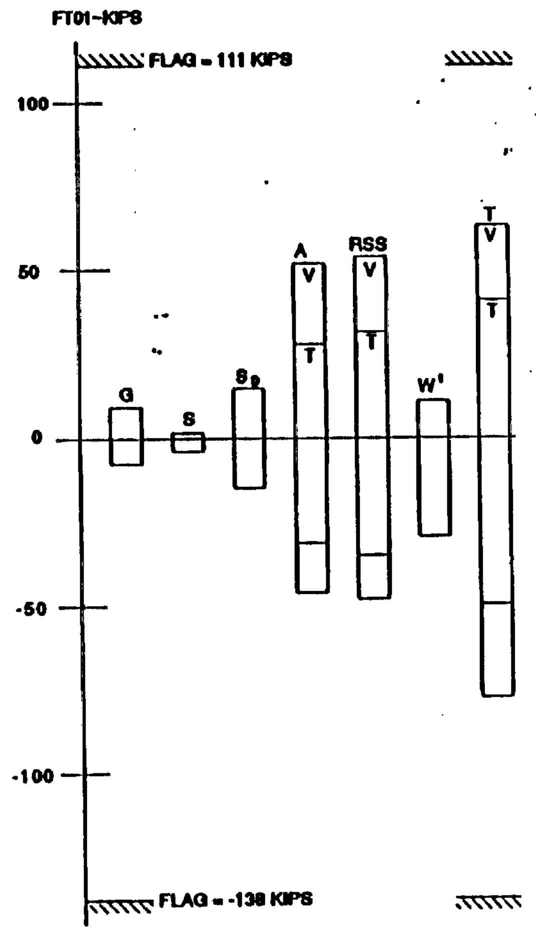


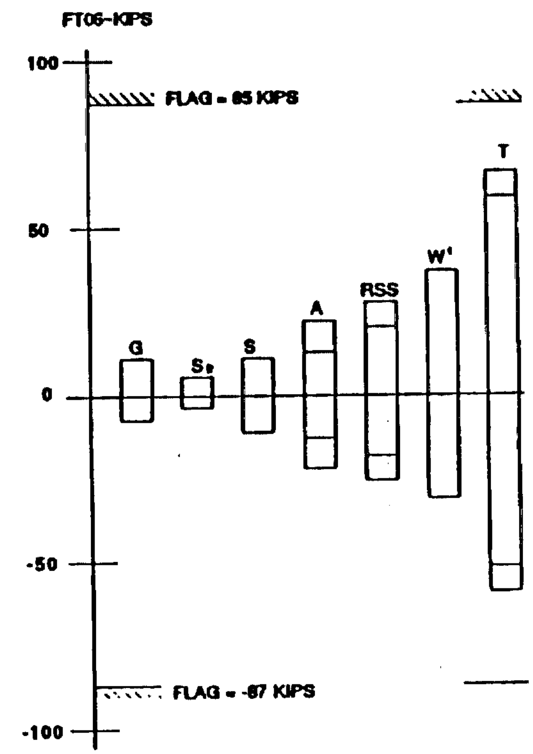




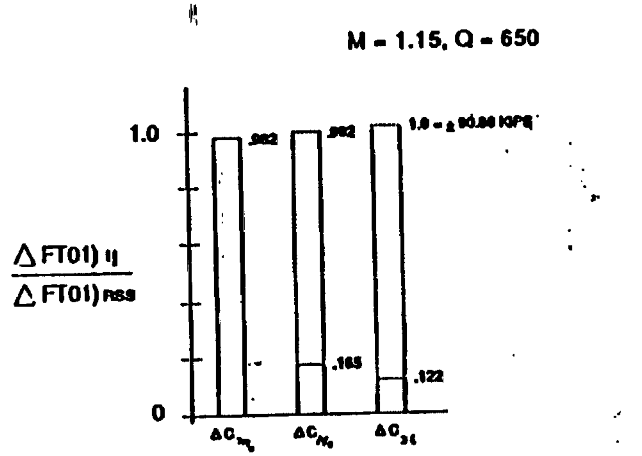
MEMBERS CAN BE EASILY FIXED

EFFECT OF AERODYNAMICS ON MAX q - LOAD CONSTRAINTS - FITTINGS

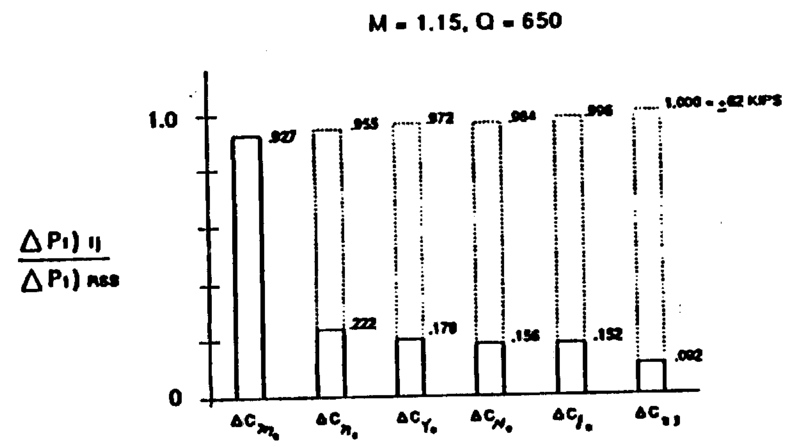




COMPONENT EFFECT ON THE AERODYNAMIC CONTRIBUTION TO THE MAX q LOAD CONSTRAINT

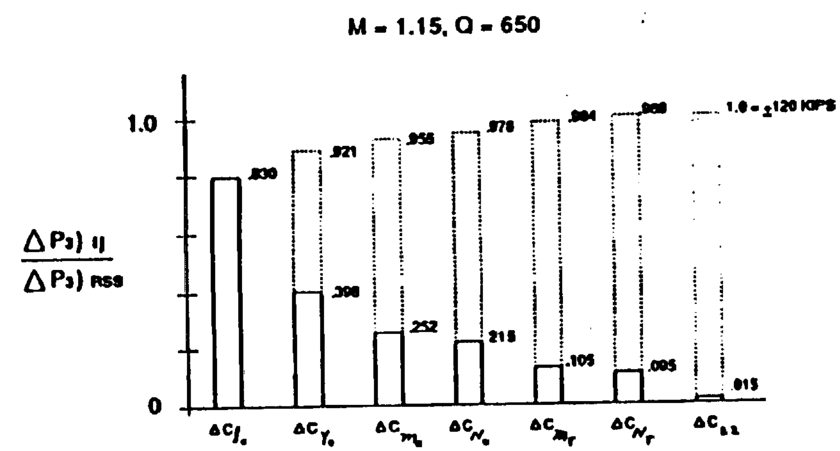


RIGID BODY FLAG LOAD = +111, -138 KIPS



ΔC = RSS OF REMAINING 23 AERO VARIATION CONTRIBUTORS

RIGID BODY FLAG LOAD = +117, -121 KIPS

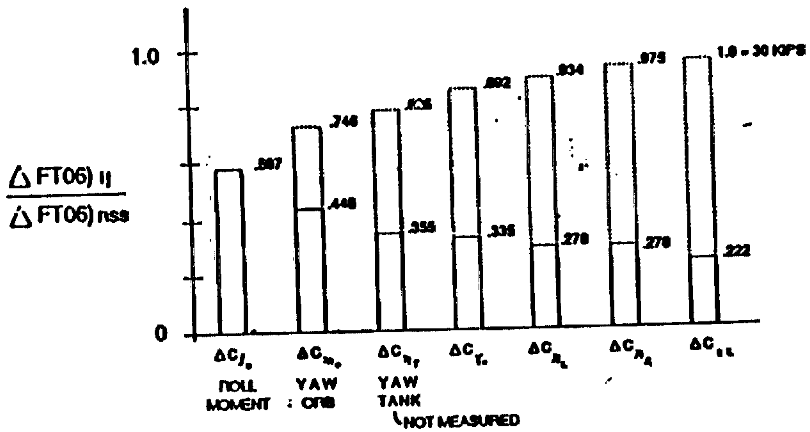


RIGID BODY FLAG LOAD = +444, -269 KIPS

ORBITER -
PITCHING MOMENT Cmo
PRIMARY CONCERN

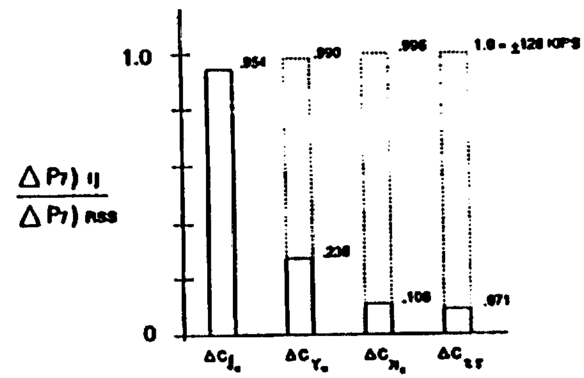
COMPONENT EFFECT ON THE AERODYNAMIC CONTRIBUTION TO THE MAX q LOAD CONSTRAINT

M = 1.15, Q = 650



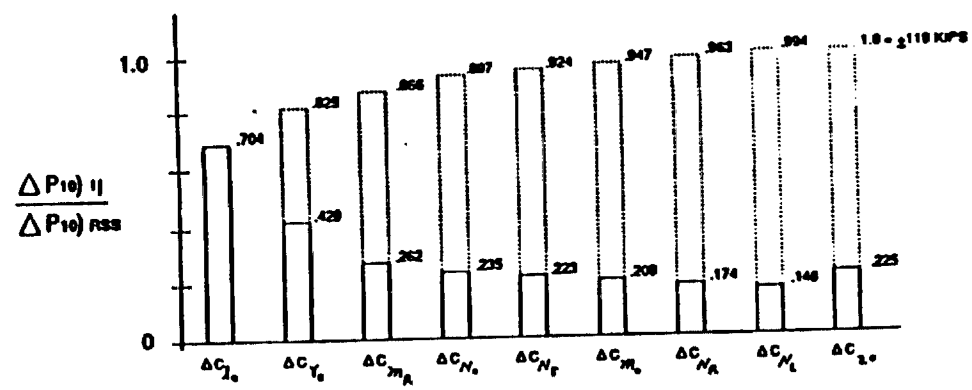
RIGID BODY FLAG LOAD = +85, -87 KIPS

M = 1.15, Q = 650



RIGID BODY FLAG LOAD = +117, -121 KIPS

M = 1.15, Q = 650

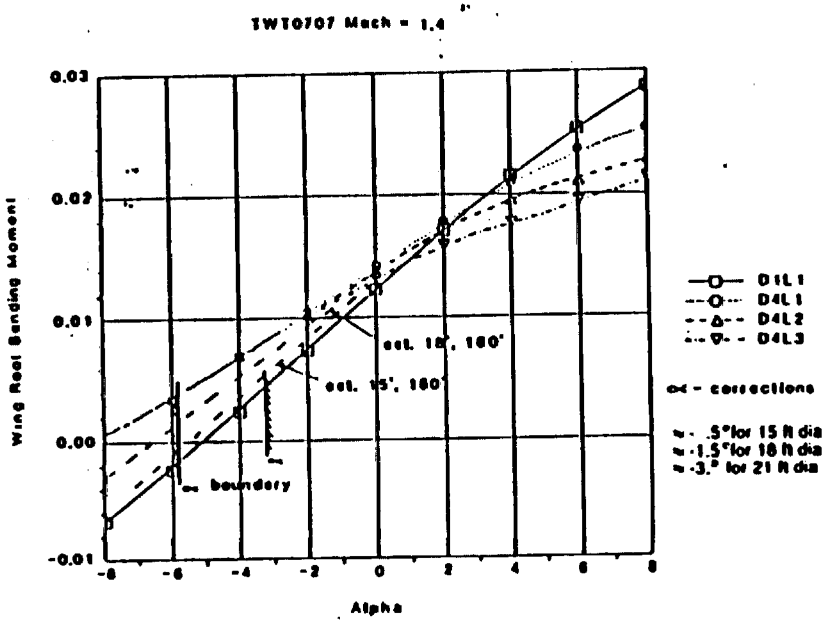


RIGID BODY FLAG LOAD = +215, -285

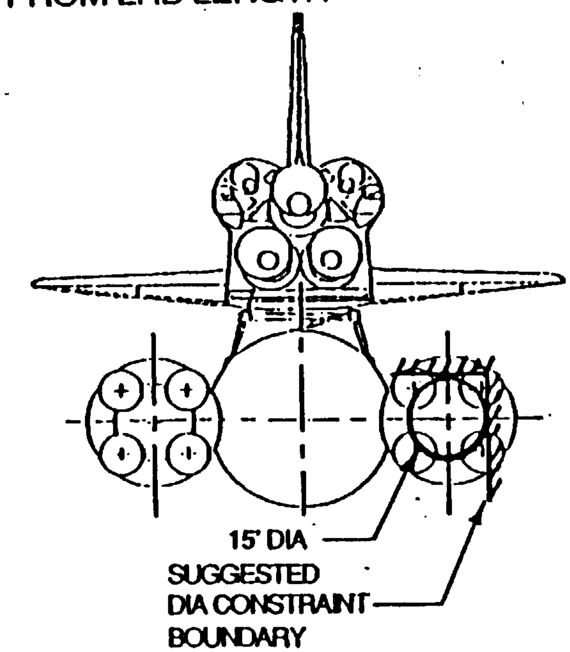
ORBITER -
PITCHING MOMENT Cmo
PRIMARY CONCERN

EFFECT OF LRB LENGTH AND DI. INCREASE ON MAX q LOADS

- THE PRIMARY CONCERNS
  - ORBITER WING LOADS
  - ORBITER PITCHING MOMENT
  - ORBITER ROLLING MOMENT (MINIMUM)



- MSFC TEST SHOWED SIGNIFICANT EFFECT ON THE ORBITER AERODYNAMICS DUE TO LRB DIAMETER CHANGES BUT NO MAJOR EFFECTS FROM LRB LENGTH



- CONCLUSION - LIMIT TANK DIAMETER THAT BRINGS LRB NO CLOSER TO ORBITER THAN AN EQU ELEMENT 15FT DIA SRB

EVALUATIONS OF CONFIGURATION FROM MAX q - CONSIDERATION

- OPTION 1
  - THE RECOMMENDED MAX 15' DIAMETER CONSTRAINT SHOULD BE APPLIED TO THE HAMMER-HEAD - UNLESS WIND TUNNEL DATA IS OBTAINED
- OPTION 2
  - STRAKES ARE NOT RECOMMENDED AS A METHOD TO ALLOW LRB DIAMETERS GREATER THAN 15' UNLESS WIND TUNNEL DATA IS OBTAINED
- OPTION 3
  - INCREASING THE ORBITER INCIDENCE ANGLE IS NOT RECOMMENDED DUE TO PAYLOAD BAY DOOR STRUCTURE LOAD AT NEGATIVE ANGLE-OF-ATTACK.
- OPTION 4
  - LOOKS REASONABLE FOR AERO LOADS AT MAX q
- OPTION 5
  - LOOKS REASONABLE FOR AERO LOADS AT MAX q
    - ADDITIONAL DATA WILL BE REQUIRED ON LOX TANK
    - MORE FORWARD CENTER OF PRESSURE CAN BE HANDLED BY FLIGHT CONTROL SYSTEM
- OPTION 6
  - SHOULD NOT ADVERSELY EFFECT THE MAX q WING LOADS
- OPTION 7
  - SHOULD NOT ADVERSELY EFFECT THE MAX q WING LOADS
- OPTION 8
  - SHOULD BE ACCEPTABLE FROM MAX q LOADING

NSTS Liquid Rocket Booster

General Dynamics Corporation

Task I

Vehicle Systems Effects

Prepared By

Eagle Engineering Incorporated

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Introduction

The Liquid Rocket Booster study conducted by The Space Systems Division of General Dynamics Corporation was intended to identify concepts for Liquid Rockets to replace the current NSTS Solid Rocket Boosters with minimum impact to the on-going Shuttle Program and increased reliability and performance capability. Additional objectives of the study were to provide pressure fed propulsion system concepts for consideration and to provide baseline data for potential ALS or Stand-Alone booster configurations.

Eagle Engineering, Inc. provided technical support to General Dynamics during this study. A set of specific tasks were identified to be completed by Eagle. As the study progressed the effort was re-oriented to satisfy the demands of changing groundrules. The data in this report reflects activity under the original task arrangement and the revised groundrules. Significant support was also provided to General Dynamics in development of the LRB integration plan.

Task 1 Summary Report

Task 1 of the STS Liquid Rocket Booster (LRB) study required Eagle Engineering, Inc. to supply current data relative to the Space Shuttle vehicle and systems affected by an LRB substitution.

The material transmitted consisted of selected data from NASA documents including the Space Shuttle Flight and Ground Systems Specification (JSC 07700, Vol. X), the Shuttle Operational Data Book (SD73-SH-01801i), and Interface Control Documents, as well as other NASA documents and records.

Table 1 lists those data products which were submitted individually due either to General Dynamics specific request or in compliance with the basic requirement. Much of this material was extracted from the Systems Integration Review (SIR), and Ascent Flight Systems Integration Review (AFSIG) meeting minutes and presentation material, as well as various other sources.

Table II lists those data products applicable to SRB/LRB that were part of the return to flight Design Certification Review (DCR) being conducted to certify the Shuttle System for resuming the flight program.

This task was extended to provide data products as the need arose.

Data Transmittals to GDSS
Liquid Rocket Booster Study
Table I

Item	
LRB Studies, Shuttle Constraints Summary (Huntsville)	10-14-87
JSC 07700 SRB requirements and applicability to LRB	10-30-87
JSC critical design review data relative to crew escape	11-05-87
STS-26 trajectory design data package	11-09-87
Reference mission descriptions and related configuration and performance data	11-09-87
WTR PRM-4 baseline trajectory groundrules	11-09-87
STS-51-L fluids budget, weight and C.G. data	11-09-87
LRB effect of increased length and diameter on orbiter loads	11-16-87
Action item: Booster aerodynamics and flight to wind tunnel comparison	11-16-87
SSME POGO suppressor information	11-16-87
Eagle report 86-150 - SSME Startup Transient at WTR	11-16-87
LRB heating data and STS-26 abort planning	11-17-87
Shuttle ascent key events from STS 61C	11-19-87
Design issues - review comments	11-19-87
SSME ignition timing and propellant usage data	11-20-87
Ascent abort gaps from STS 5, 6, & 9	11-23-87
LRB heating data	11-23-77
Abort boundaries STS 4 & 5	11-25-87
Intact abort windows	11-25-87
NSTS aerodynamics co-efficients (Hard copy and floppy disk)	11-25-87

Table I (Cont.)

LRB Constraints Data Book	11-30-87
SRB/Shuttle/ET Longitudinal Aerodynamics	12-01-87
Hold down post deflections	12-14-87
DCR material (see separate list)	01-08-88
Orbiter/ET ICD, STS ICD-2-12001	01-13-88
SRB/ET ICD, STS ICD-2-24001	01-13-88
Relative Impact of LRB Candidates on Flight Control	02-25-88

Design Certification Review Transmittals
Liquid Rocket Booster Study
Table II

STS 84-0575	Space Shuttle IVBC-3 Aerodynamic Heating Data Book, SRB-Ascent, May 24, 1984.
STS 84-0;259	IVBC-3: SRB Plume Heating Data Book, October 1984.
STS 82-0570	Space Shuttle System, SRB Separation Verification for Operations, November 1982.
SD 74-SH-0144E	Space Shuttle Program Thermal Interfaces Design Data Book IVBC-3, preliminary copy, September 1987.
SD 73-SH-0178	Space Shuttle Flight Systems Performance Data Book, Volume 1 C - ascent, SDM Baseline, December 1975.
STS 84-0044	Integrated Vehicle Baseline Characterization (IVBC-3), Ascent GN&C Summary Report, Volume 1: Basic & Appendixes A through D; and Volume 2: Appendixes E & F, April 1984.

Transmittal of IVBC-3 Roll Maneuver Limit Loads for Steel Case SRB's.

IVBC-3 and FWC (Filament Wound Case), Cycle 3, Orbiter High Q Loads, Revision D.

Transmittal of Revised IVBC-3 and Filament Wound Case (FWC), Cycle 3, External Tank and Solid Rocket Booster High Q Loads Documentation, Revision A.

Additional IVBC-3 Solid Rocket Booster High Q Loads.

Update to the Overpressure Data Book, STS 83-0540, containing:

1) 87-100 SRB IOP Environment for Pc (Max) Specification Requirements (Feb. 16, 1987),

2) 87-409 Methodology for Incorporating Pc Max. Change in SRB Ignition Overpressure Environment (March 27, 1987).

Transmittal of Aerodynamic Data Updates to the Aerodynamics Data Book, SD72-SH-0060-2L.

Transmittal of Shuttle Liftoff Loads for VAFB Launches with Cycle 3 Filament Wound Case Boosters (EMS 280-205-354).

Nominal Position and Maximum Excursions in X,Y, and Z Axes for Design of a Ground Umbilical/Bottom of SRB Skirt Interface.

Additional IVBC-3 High Q Orbiter/ET Attach Load Conditions for Orbiter Assessment.

Table II (Cont.)

SRB Time Consistent Liftoff Loads for Design Certification Review.

IVBC-3 Post High Q Loads.

Shuttle Liftoff Loads for Design Certification Review.

NSTS Liquid Rocket Booster

General Dynamics Corporation

Task II

Preliminary Vehicle and Facilities Impacts Assessments and Parametric Data Generation Summary Report

Prepared By

Eagle Engineering Incorporated

Preliminary Vehicle and Facilities Impacts Assessments and Parametric Data Generation

1.0 Introduction

2.0 Purpose

3.0 Summary of LRB Groundrules, Constraints and Design Factors

4.0 LRB Impact to NSTS Ground and Flight Systems and Operations

4.1 Aerothermodynamic Evaluation of LRB Configuration

4.2 Flight Operations Evaluation of LRB Configurations

4.3 Integrated Structural Loads and Dynamics Evaluation of LRB Configurations

4.4 Main Propulsion System Evaluation of LRB Configurations

4.5 Integrated Ground Systems Evaluation of LRB Configurations

4.6 Integrated Avionics Evaluation of LRB Configurations

4.7 Integrated Guidance, Navigation and Control Systems Evaluation of LRB Configurations

4.8 LRB Cost Impacts

Preliminary Vehicle and Facilities Impacts Assessments and Parametric Data Generation

1.0 Introduction

The primary emphasis of the Liquid Rocket Booster (LRB) study has been to define an alternate boost stage launch system for the Space Shuttle with enhanced safety, reliability, and performance characteristics. Additionally, the LRB must be integratable with Space Shuttle ground and flight systems with minimum impact. The purpose of this task (Task II) therefore is to evaluate and compare shuttle impacts of candidate LRB configuration in concert with overall trades of analysis activity.

The initial plan included Shuttle assessments of all proposed configurations and was planned to be completed within three months. The effort was delayed due to configuration definition and the down-selection process occurring simultaneously. The activity was redefined for the second half of the study to concentrate on three selected configurations with emphasis on flight loads, separation dynamics, and cost comparison. This report covers only the first half activity.

2.0 Purpose

The purpose of this report is to provide the status of Task II through March 31, 1988. Tasks to define the impacts of ascent flight loads, booster separation, and costs are in process and will be included in the final report. The five configurations being assessed, (See Figure 1) are as follows:

Configuration	Propellant	Engine	Principle Features
1B	LO2/RP-1	Pressure-Fed	Closest to SRB Geometric parameters
5A	LO2/LH2	Pump-Fed	Same propellant as current SSME's
5D	LO2/RP-1	Pump-Fed	
5J	LO@/LH2	NSTS SSME	
5K	LO2/RP-1	Saturn F-1	

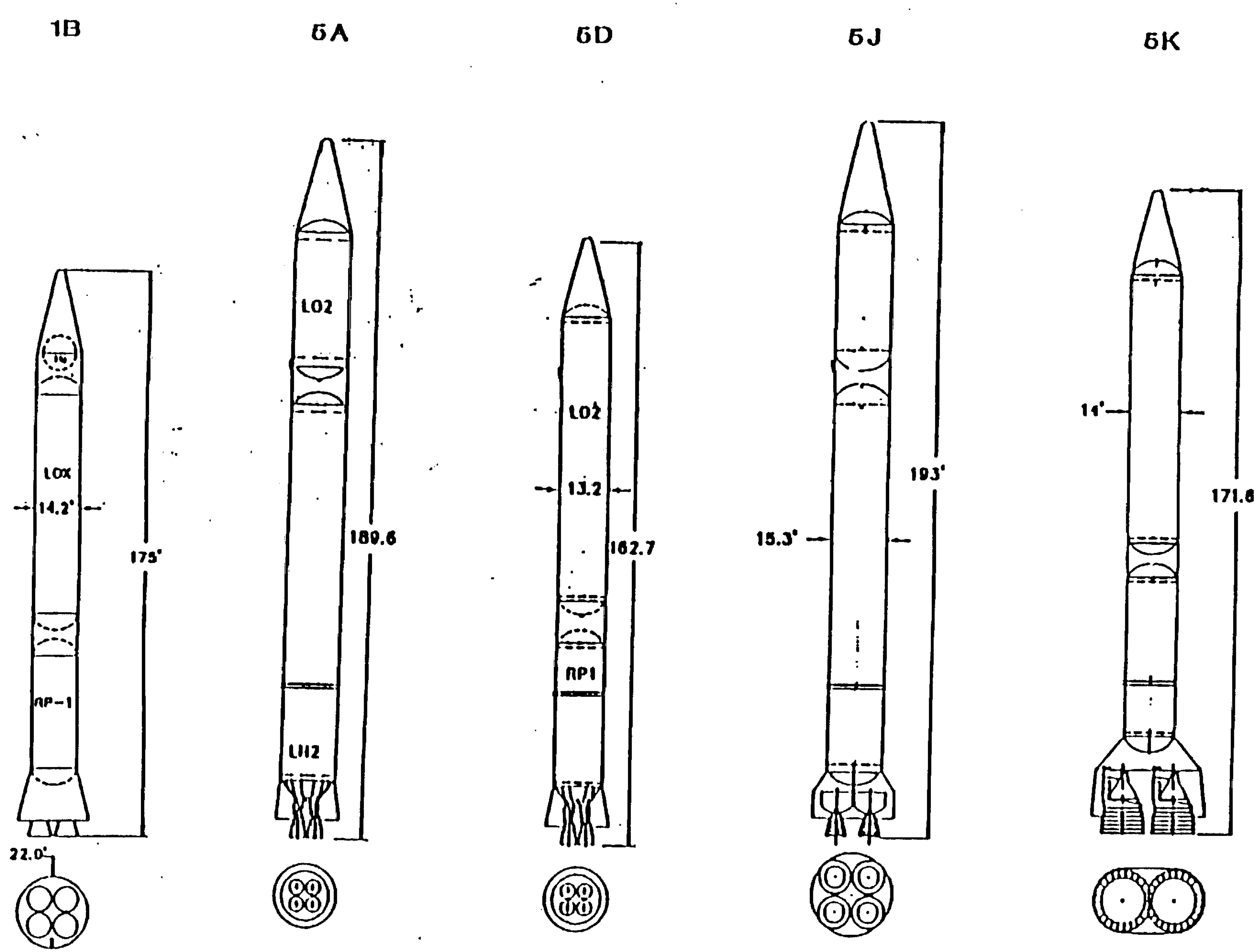
3.0 Summary of LRB Groundrules, Constraints and Design Factors

The primary groundrules utilized in assessing the impact of the LRB designs on the NSTS vehicle, facilities, and operations are:

(1) Provide capability to launch 70000 pounds to 150 nm orbit.

(2) Provide safe abort capability with one LRB or SSME engine out with a goal to be capable of abort to 105 nm orbit with one engine out.

LRB CONFIGURATIONS



Fi e 1

(3) Use existing NSTS constraints for maximum aerodynamic pressure, maximum gravity forces; day-of-launch winds; launch probability; systems dispersions; flight performance reserves; Orbiter and External Tank structural design, etc.

(4) No redesign of the Orbiter and ET thermal protection system (TPS).

(5) No redesign of the ET interface attachments.

(6) Minimum impact to Shuttle avionics and software design.

(7) Minimal changes to KSC facilities and GSE.

(8) Retain current Shuttle vehicle stability and control margins.

The primary LRB factors that must be considered in assessing these impacts are:

(1) Diameter
- Proximity and moldline effects on Orbiter and ET.
- Aeroheating impact on Orbiter and ET thermal protection system (TPS).
- Utilization of existing ET interface struts and fittings.
- Modification requirements for the mobile launch platform (ML).
- Orbiter structural loads impacts including wing (aerodynamic effects).

(2) Length
- Aeroelastic effects.
- LRB/ET forward attach loads.
- Flight control system effects.
- Modification requirements for KSC facilities/GSE. (LRB processing handling, assembly, etc.)

(3) Number of Engines
- Thrust vector control (TVC) authority.
- Abort options.
- MLP flame hole modifications.
- Startup/shutdown sequence.
- Safety/Reliability.
- Integrated avionics requirements.
- Lift-off thrust-to-weight ratio.

(4) Mass Properties
- Propellant tank arrangement.
- TVC authority.
- LRB/ET interface loads.

(5) Type of Propellant
- Performance.
- Atmosphere quality.

- Water quality.
- Plants and animal life.
- Noise/acoustics level.
- Handling/loading/spills.
- Transportation.
- Ground Handling and Loading.

4.0 LRB Impact to NSTS Ground and Flight Systems and Operations

4.1 Aerothermodynamic Evaluation of LRB Configurations

The LRB configurations were assessed to determine the impact on the heating to the baseline shuttle system, primarily the Orbiter and ET thermal protection system (TPS). All LRB configurations are longer than the SRB, and were evaluated by examining the location of each LRB nose tip relative to the ET. the resultant shock impingement from the LRB nose onto the higher heating regions of the ET forebody was assessed for its impact on the baseline TPS. The longer LRB's are thought to have minimal effect on the Orbiter forebody TPS. A qualitative assessment was made of the plume effects on the base region of the Shuttle system.

Proposed changes to the Shuttle system could impact the baseline TPS design if heating rates produced by these changes exceed the existing material capabilities. Thus, examination of the ET TPS layout and comparisons of heating rates for the ET design with those predicted with the LRB's were made. The majority of the tank is covered with a spray-on-foam insulator (SOFI), which has a heating rate limit of 10 BTU/sq-ft-sec. Various thicknesses are tabulated ranging from 2.15 inches at station 371 ($x/1 = 0.024$) to 1.0 inch (required to protect against ice/frost on the pad) at station 570 ($x/1 = 13$). A Super Light Ablator (SLA), which can withstand heating rates as high as 30 BTU/sq-ft-sec, is located under the feedlines and in the forward region of the nose which experience high heating rates from the shock off of the 30/10 degree conical tip. A slightly denser spray-on-foam, NCFI, covers the ET base region.

Two assumptions were made in developing the predicted rates for the LRB's. One is that they are attached at the same ET location as the SRB, and two, that the shock impingement distance, which occurs approximately 0.055 to 0.075 ET body lengths aft of the SRB nose tip, forward movement of the shock impingement location, the baseline value of the shock on the intertank is removed. The magnitude of the protuberance effect of the attachment may be lower for the LRB's but not felt. The high heating observed on the intertank is due to the shock from the SRB compound by the presence of the ET/SRB attachment. However, the intertank region is protected only with CPR due to the massive structure being able to tolerate the high heating.

Examination of Configurations 5A, 5D, and 5K show that a small region on the ET ogive would experience heating rates that exceed the SOFI limit and would require a modification to the TPS, such as a strip of SLA. The differences of the effect of these three concepts on the ET is small, with Configuration 5K being the smallest. The least TPS impact would be from Configuration 1B. No SLA would be required but perhaps concepts 1B and 5A would not be an additional TPS impact but may require a structural change to the intertank. The largest TPS impact would be experienced with Configuration 5J. The location of the nose tip is such that the shock impinges exactly on the nose region that experiences the high heating from the ET conical tip shock impingement. The possibility of the two phases compounding the flow field effect resulted in a factor of 2 differences predicted for the LRB effect peak value. If the maximum heating rate is 40 BTU per square-foot-second then an ablator, such as MA25 could replace the SLA. If the heating rate is as high as 80 BTU per square-foot-second, this exceeds the MA25 capability of 75 and might require a major TPS modification. A change to the length would be recommended.

Only a qualitative assessment can be made of the plume environment on the base region of the shuttle pending further definition of the concepts. A detailed analysis will be required once the configurations are better defined. Visual inspection of the engine arrangements and associated vehicle configuration indicate little, if any, differences would be detected among the five concepts.

The primary factors effecting plume base heating are: number of engines; nozzle area ratio; combustion chamber pressure; nozzle exit location; plume radiation characteristics; and vehicle base pressure. The environments are likely to be reduced for the LH2/LO2 propellants and increased for the LO2/RP-1 propellants. State-of-the-art ablators are available in the event the ET LH2 tank bulkhead requires additional thermal protection. Total vehicle base pressure must be evaluated to assure that the selected configuration does not seriously affect convective base heating environments. However, if the LRB engine plumes are located to stay within the current SRB plume boundaries at each altitude, then one could assume that the induced aerodynamic effects on the Orbiter/ET would be similar.

In summary, the thermal examination of the LRB concepts' effect on the shuttle system indicated Configuration 1B as having the least impact on the ET TPS, and Configuration 5J as having the largest. The remaining three concepts, 5A, 5D and 5K, would require a small strip of ablator material, possibly SLA, to the ET ogive in order to accommodate their thermal impact. No discriminators for the plume impact are obvious among the concepts; however, Configuration 5K appears to be the least attractive.

4.2 Flight Operations Evaluation of LRB Configurations

4.2.1 Flight Rules and Procedures

The majority of flight operations impacts involve changes to flight operations procedures. With four throttleable engines per liquid booster, there are more possible actions to consider. New flight rules and procedures must be developed to consider all options.

The flight rules and procedures changes for a liquid rocket booster system will be much more significant than a typical engine modification. New flight techniques, failure modes, and procedures for operating and managing the liquid boosters must be developed and evaluated. Updates to the launch commit criteria and the redundant set launch sequencer must be addressed.

Abort rules must be rewritten to reflect the enhanced abort capabilities made possible by liquid rocket boosters. New abort rules will be a significant part of the new flight operations procedures required.

4.2.2 Software

New flight operations software must be developed, tested, and certified to reflect the changes caused by solid rocket boosters. Software development for LRB's will be more extensive than for SRB's due to more complex valves, pumps, liquid level, slosh effects, etc., and to the increased number of engines per booster. Extensive modifications will have to be made to the software and the software must be taken through a rigorous verification process before flight. The control functions of liquid rocket boosters (e.g., valves, flows, pumps, temperatures, pressures, etc.) are more complex than those of solid rocket boosters, the orbiter pre-launch, pad switch-over and orbiter ascent phase software requirements for monitoring and controlling the LRB's will be more complex.

Another factor contributing to increased software development is the number of LRB engines. Four throttleable engines per booster adds to both the complexity and reliability of the STS system. Onboard software must be developed to prevent a thrust imbalance caused by the loss or degradation of an LRB engine.

Each of the proposed liquid rocket booster concepts all orbiter capability with loss of one LRB engine and enhances the abort capabilities with orbiter main engine degradation. New software must be developed to reflect these new flight capabilities and procedures. Software to throttle LRB engines must be developed.

The larger sizes of the liquid rocket booster concept studied will produce new aerodynamic forces and moments for which the orbiter ascent flight control software will have to compensate. New orbiter software builds, integration, test, and extensive verification will be required regardless which liquid rocket booster design is chosen. Software compensation for slosh in the new LRB tanks will have to be developed and tested.

If the liquid rocket booster has more than two controlled thrusting nozzles, then additional ascent thrust vector control drivers will have to be implemented in the orbiter avionics. This requirement in turn would impose additional complexity to the orbiter's ascent flight control software.

Studies will have to be made to see if the addition of LRB throttling capability and the possibility of different LRB thrust profiles change the area over which the external tank operates. Possible impacts of the proposed liquid rocket booster system on the Shuttle Avionics Integration Laboratory (SAIL), Shuttle simulators, Software Production Facility, System Integration Schedule D Contract, and on the STS Operations Contract (STSOC) must be evaluated.

4.2.3 Training and Simulations

Training and simulations must be updated for flight crews and flight control operators to learn in the new procedures required by the more complex control functions of liquid rocket boosters. The new abort capabilities will change the nature of abort simulations, resulting in fewer Trans-Oceanic Abort Landing (TAL) and Return to Launch Site (RTLS) simulations and more Abort Once Around (AOA) and Abort to Orbit (ATO) simulations. New malfunction procedures for liquid rocket booster leaks or hardware failure must be incorporated into the simulations. The orbiter crew must be trained to use a few new displays, monitors, and caution and warning indicators, as well as some new manual override switches. Initial hardware training costs will include updating the displays, controls, and the caution and warning lights in the orbiter mock-ups, training consoles, and in the Mission procedures.

4.2.4 Payload Integration

Payload integration will not be impacted by the substitution of liquid rocket boosters if the liftoff and ascent loads environment of the Shuttle System using liquid rocket boosters matches or is within the present envelope of the system using solid rocket boosters. The current liftoff and ascent loads environment is described in NSTS 07700, Volume 14, Attachment 1 (ICD-2-19001). If the loads are within the present envelope, the substitution will be transparent to the payload community.

4.2.5 Pre- and Post-Flight Analysis

Flight analysis will be required to assess impacts in several areas. Modifications will be required throughout the entire onboard guidance system. Ascent procedures will have to be rewritten and evaluated. The abort region determinator (ARD), which defines actual abort times based on vehicle performance, must be expanded to accommodate the increased engine number and complexity. Greater Abort to Orbit (ATO) capability will minimize Return to Launch Site (RTLS) and Trans-Oceanic Abort Landing (TAL) considerations, and may eventually simplify ascent procedures once the new software and procedures have been evaluated.

4.2.6 Real-Time Flight Control Impacts

A LRB system would require at least one new display similar to that for the Space Shuttle main engines. The substitution of more complex and versatile liquid rocket boosters will require the addition of one new backroom booster console, specializing in the valves, flows, pumps, temperatures, pressures, and malfunction procedures of liquid rocket boosters during pre-launch, launch and ascent phases.

The Booster flight control position is responsible for monitoring the main propulsion system (MPS) including the Space Shuttle main engines, external tank, and solid rocket boosters during pre-launch, launch and ascent phases.

In switching to any of the proposed liquid booster systems, the complexity of the Booster console operator's work will depend on the number of possible actions, and on the amount covered by software. Also, the orbiter crew needs the capability to manually shut down the LRB engines.

Real-time data transmitted to the ground about the liquid rocket boosters might require a separate transmitter, located on a booster. In this case, electromagnetic interference concerns must be checked pre-flight. However, this small increased downlist data requirement during ascent would have very little impact on flight control communications.

4.3 Integrated Structural Loads and Dynamics Evaluation of LRB Configurations

4.3.1 Plume Ignition Overpressure

The primary factors effecting plume ignition overpressure on the Orbiter base heat shield are: number of engines; thrust buildup rate; and engine ignition sequence. The orbiter heat shield structural limit is approximately 1.3 psi. The overpressure generated by the SSME's is significantly below this limit. The overpressure generated by the SRB's exceed the 1.3 psi limit, thus requiring overpressure control capability designed into the ground launch facilities. Although the overpressure generated by the LRB's must be evaluated, there are several factors that influence the magnitude of the LRB ignition overpressure which may negate the requirement for overpressure control. These are the slower thrust buildup rate, lower thrust level engines, and the engine ignition sequence.

4.3.2 Acoustic Environment Effects

The acoustic environment generated by the LRB engines is a factor of: number of engines; nozzle area ratio; engine operating pressure; and propellant combination. Most Shuttle payloads are sensitive to acoustic environment. However, most payloads launched on the Shuttle are designed to be compatible with the current Shuttle acoustic environment. Some Shuttle hardware also has upper operating limits. Both the Orbiter SSME's and SRB's are major sources of high acoustics, thus the combined effects must be considered. Currently, MLP high flow capacity water spray systems control acoustic levels prior to lift-off.

Such a system will be required for the LRB; however, this does not appear to be a problem for any of the configurations assessed. The current Shuttle experiences maximum acoustics after lift-off at an altitude of approximately 80 feet. Test and analyses will be required to assure acceptable environments exist or if corrective measures must be implemented. Meeting current interface limits with payloads will be a prime consideration.

4.3.3 Vehicle Dynamics Analysis/POGO Control

The current Shuttle has a POGO suppression system. The dynamic response with the LRB will require additional analyses/testing. Changes to the current POGO system are anticipated since active suppression will probably be a requirement for the LRB.

4.3.4 Engine Start Sequence/Stagger Time

The start sequence/stagger start time for the total Shuttle will have to be assessed for vehicle/facility optimization.

4.3.5 Dynamics of LRB Separation from Shuttle

Thrust from the LRB's can be terminated or reduced, thus permitting separation from the Orbiter at different times during flight, which was not the case with the SRB's. It will be necessary to develop analysis and test data relating to separation characteristics of the LRB as a function of generally different ascent scenarios including intact and contingency abort modes. This will be one of the major system areas that will require full recertification/reverification through test and analyses.

4.3.6 Effect of LRB Length and Diameter on Structural Loads

The primary concern with changing the booster mold lines from the current SRB configuration is the effect of aerodynamic loading on the Orbiter wing and Orbiter/ET attach fittings and struts during flight through the maximum dynamic pressure regime. The results of tests conducted by MSFC indicate that there is a significant effect on the Orbiter aerodynamics due to LRB diameter. The diameter should be limited to 15 feet unless additional wind tunnel data is obtained. Other observations are:

(1) Strakes should not be used as a method to permit LRB diameters greater than 15 feet unless additional wind tunnel data is obtained.

(2) Increasing the Orbiter incidence angle is not recommended due to increased payload bay door structural loads at negative angle-of-attack.

4.3.7 Load Factor

Due to potentially higher load factors with LRB's during first stage, the effect on ET tank pressure loads and structural loads may require additional ascent flight constraints.

4.3.8 Pre-Launch and Lift-off Environment

The current NSTS configuration using SRB's is very sensitive to the ignition sequence. During pre-launch operations the SSME start causes large excursions in the bending moment at the base of the stack which is resisted at the hold-down posts. At SRB ignition and release the stack responds to the residual moment in a manner called "twang". The twang response couples with the rapid SRB thrust buildup response and the SRB ignition overpressure. The current ignition sequence is designed to provide acceptable pre-launch loads and vehicle excursions without increasing the lift-off loads.

The LRB-equipped Shuttle should provide a reduced thrust build-up and overpressure environment, but is expected to have lower stiffness, and a higher excursion envelope. A combination of MLP redesign and revised ignition sequence may offset the excursions, but additional provisions may also be required.

The lower bending frequency expected will also require significant control stability analyses for slosh damping and other concerns during the early flight phase.

4.4 Main Propulsion System Evaluation of LRB Configuration

4.4.1 LH2/LO2 Configuration - Engine H2 Lag at Shutdown

Unburned H2 exits the SSME after the LO2 main valve has bee closed at engine shutdown. Some of the H2 is unburned, creating an explosion potential. A new engine for the LRB

LH2/LO2 configuration will probably have similar characteristics. The H2 quantity for the SSME's can be more than 150 pounds per engine. This problem is currently being assessed for the SSME's, and may be applicable to the LRB. Potential testing and analyses may be required to resolve this issue for the LRB.

4.4.2 LH2/LO2 Configuration - Pre-ignition H2 Purge

The SSME start sequence utilized a short H2 lead which is dumped through the engine nozzle. Accumulation below the engine followed by ignition can cause unacceptable overpressure. A H2 burn-off system has been implemented for the SSME's to assure an explosive accumulation of H2 below the engines does not occur prior to engine ignition. A similar system will probably be required for a LRB LH2/LO2 engine.

4.4.3 MPS Abort Analyses

The LRB will result in a number of new options for Shuttle. Thermal/fluid analyses for some of the abort conditions will be required to determine abort capability for both intact abort requirements and for enhancement of contingency abort capability.

4.5 Integrated Ground Systems Evaluation of LRB Configuration

4.5.1 MLP Modifications

Engine exhaust gas from LRB nozzles will be more diffused than SRB exhaust gases. A larger hole in the MLP may be required for this gas flow to avoid direct impingement. Modifications will also be required for new pad venting and work platform requirements.

4.5.2 Exhaust Trench Modifications

More study is required to determine the degree of impact.

4.5.3 Prelaunch Operations for the Engine, Intertank, and Nose Cap Volumes

Large quantities of thermally controlled N2 must be provided anytime cold and/or explosive propellants are onboard prior to vehicle lift-off. Air (possibly warmed) must be provided to purge the engine compartment for work crews. Systems include gas storage, gas heating, duct transport system, and control/monitoring instrumentation. Engine controllers, and other computers and electronic/electrical equipment generally have both low/high thermal limits, thus creating a potentially unacceptable explosive environment. The LRB configurations having no H2 have less of a thermal problem, thus require less heat. The explosive potential and monitoring requirements are less with RP propellants than with H2. The intertank and nose cap areas are of less concern as they are smaller volumes, and have less equipment and leak sources.

4.5.4 Prelaunch Environment

The probability of ice/frost formations on the LRB is similar to the ET. Thus the current Shuttle ice/debris requirements for the ET will also apply to the LRB, potentially impacting LRB TPS designs. Uninsulated RP tanks have large circumferential temperature distribution, possibly effecting structural response/design, plus non-uniform propellant heating with the potential for inverse propellant thermal stratification. However, this does not appear to be a significant LRB design problem.

4.5.5 Propellant Storage and Handling

A comparison of LH2 and RP propellant storage and handling characteristics at KSC is not completed. However, there appears to be very little difference in activating either. The primary advantages of RP propellants over LH2 are that no burn pond or vacuum jacketed lines are required, and is generally less complex to handle. Also, RP propellants can be loaded prior to flight day and require no helium tank purge.

4.5.6 Ground/Vehicle System for Propellant Tank Pressurization Prior to Engine Start

The Shuttle vehicle LH2, LH2, and RP propellant tanks for a pressure-fed LRB configuration will require pressurization prior to engine start. This will probably be accomplished with helium or nitrogen. The current ground helium system for supplying the Orbiter will probably be inadequate to meet LRB requirements. An interface with the onboard and ground for this system will be a new requirement since this interface does not exist for the current configuration.

4.5.7 MLP Holddown Release Mechanism

The holddown release mechanism and associated systems will have to be modified to incorporate new LRB requirements. These are primarily modified to incorporate new LRB requirements. These are primarily associated with the requirement to delay release until the health of all of the LRB engines has been verified, and the communication of these data to the Orbiter/ground controller. Additional studies are required to determine the optimum release procedure.

4.5.8 Pneumatic Supply

The LRB will increase the requirements for pressurized helium and nitrogen for various engine seal and cavity purges; valve actuation systems; and various flight pressurant gases. The capability of the current system will probably have to be increased to meet these requirements. Also, provisions must be incorporated to provide the status of these systems to ground control during preflight and ascent operations.

4.5.9 LO2 Geysering Suppression

Gas formation in the LO2 system can result in large surges which can be highly destructive. The critical phases are:

(1) During the initial propellant loading prior to line/vehicle hardware chill and before any significant quantities of liquid are in the vehicle lines.

(2) Once a significant quantity of liquid is in the lines or lines and vehicle.

The Shuttle has defined ground handling and loading procedures that prevent geysering in the ET. This will have to be assessed for the LRB, as the problem becomes very complex during loading, preflight and flight for multi-line vehicles with independent feed lines.

4.6 Integrated Avionics Evaluation of LRB Configurations

4.6.1 MPS Operation During Flight and Shutdown

Without adequate communication between the LRB and Orbiter to maximize performance, flexibility, and safety, the LRB becomes little more than an SRB. Communications for flight control existed for the SRB; however, it becomes more complex for the LRB with more engines, engine out, and the potential for variable thrust capability. Some of the many considerations include: vehicle control; vehicle structural loading capability; variable payload weights, various abort capabilities, etc. Minimizing the impact to the Shuttle integrated avionics hardware and software in utilizing these LRB features to enhance performance and safety is a key program driver.

The DC power required by the LRB's will likely be greater than that required by the SRB's. Power for pumps and valves to route, transport, and throttle the liquid fuel and oxidizer would be expected to add to the power required for thrust vector control, rate gyros, range safety, etc. If the LRB's are retained longer during the ascent phase for improved performance, the demand for Orbiter power would be for a longer period. Dependence upon the Orbiter for DC power may be excessive.

LRB's will require a Development Flight Instrumentation (DFI) package. Flight of the DFI package during the development flights may impact the Orbiter payload bay volume; thus, the payload carrying capacity. A DFI package for LRB's may be more extensive than was the SRB DFI due to more complex valves, pumps, liquid level, slosh effects, etc. Thus, additional cables or data multiplexing schemes may be required.

If the LRB's to be substituted for the LRB's have more than two (2) controlled thrusting nozzles, then additional Ascent Thrust Vector Control (ATVC) drivers will have to be implemented in the Orbiter avionics. This requirement in turn would impose additional complexity to the Orbiter ascent flight control software. All new software will require extensive test and verification.

Substitution of LRB's with different mold lines will result in new aerodynamic forces and moments which the Orbiter ascent flight control software will have to compensate for. Thus, new Orbiter software builds, integration, test, and extensive verification will be required no matter what the LRB configuration is. Software compensation for slosh in the new LRB tanks will have to be developed, tested, etc.

Since the control functions of LRB's are more complex than SRB's, e.g., valves, flows, pumps, temperatures, pressures, etc. the Orbiter/LPS prelaunch, pad switch-over and Orbiter ascent phase software requirements for monitoring and controlling the LRB's will be more complex. Thus, it should be expected that extensive modifications will have to be made to the software and the software must be taken through a rigorous verification process.

Incorporation of Built-in Test Equipment (BITE) in a replacement LRB could result in more extensive BITE coverage due to the more complex nature of LRB's over SRB's requiring additional Orbiter and Launch Processing System (LPS) software and its verification.

4.7 Integrated GN&CS Evaluation of LRB Configurations

4.7.1 Vehicle Control During LRB Shutdown

SRB thrust mismatch during shutdown is of significant concern to vehicle control. Normal LRB operation during a similar time frame should be more favorable. For abnormal operations the situation worsens. Analysis/testing is required to develop satisfactory operational methods.

4.7.2 Requirement for TVC on the LRB

In order for the LRB to integrate into the current Shuttle configuration, TVC capability on the LRB is considered mandatory. The Orbiter design has taken advantage of weight reductions by not being burdened with any requirements for providing control muscle during boost. The fact that the SSME's are gimballed at all is due primarily to reduce loads in the Orbiter/ET attach struts. The subsequent paragraphs provide the background and justification for the current SRB requirements which can be used as a basis for establishing the TVC requirements for the selected LRB configuration.

The 5.0 degree SRB gimbal angle requirement was established from six degrees of freedom dynamics simulations, using three sigma specification value of SRB thrust mismatch at tailoff, and putting a reasonable limitation on the amount of unwanted attitude excursion that would be tolerated. Mismatch was the main driver but also considered were thrust misalignment, Orbiter engine out, winds, and a design goal of avoiding gimbal angle saturation. In the max q flight phase there is a requirement for approximately 2.0 degrees of total SRB thrust trim in the pitch plane for the sole purpose of providing the required qx bias in the mean wind condition. Adding SRB thrust misalignment, wind shear effects, avionics failure (RM) transient, and Orbiter engine failure transients (not all simultaneously) consumes practically all of the entire 5.0 degrees, with practically nothing left over for linear control. Another design goal in addition to avoiding hitting the stops due to external disturbances, was to reserve 1.0 degrees for dynamic control of propellant slosh and to respond to attitude change command from guidance.

The 5.0 degrees per second rate requirement was established originally to provide a "bare bones" capability for "dynamic loads suppression", an original Level II Program requirement. This means phase stabilized vibration and/or slosh modes. Realizing the impracticality of this design feature for higher order modes, due to prohibitive demand on the TVC and hydraulic systems, a capability limit of roughly plus or minus 0.25 degrees at 3.0 Hertz was chosen. This alone translates into the 5.0 degrees per second requirement. The 5.0 degrees per second requirement also stems from a requirement to recover from large initial conditions on attitude and/or rate error, since it can be viewed as a limit on vehicle angular acceleration rate (jerk). Limits on acceleration rate in an otherwise linear second order system, produces instability beyond some bound on initial conditions.

These and other booster TVC requirements were established through a series of meetings of the Ascent Flight Control Panel in 1973 and early 1974, resulting in the following set of requirements to be baselined:

(1) Actuator mount geometry at 45 and 135 degrees from the plane of symmetry (as opposed to 0 to 90 degrees).

(2) Square gimbal capability pattern.

(3) Design load for actuator of 130,000 pounds.

(4) 5.0 degree usable displacement in each axis simultaneously.

(5) 5.0 degrees per second simultaneously for both actuators under full load.

(6) Minimum gimbal angle acceleration capability of 2.0 radians per second at rated load.

(7) Total duty cycle of 140 degrees per motor (read single booster thrust).

These requirements were formally transmitted to the SRB Project, from Level II, on February 12, 1974.

A word of caution on vehicle configuration. Aerodynamic moment coefficients, in a body axis system of coordinates, is perhaps the most significant design driver on TVC requirements for launch vehicle, i.e., the entire stack. Ideally they should be as small as possible for pure attitude control, but in the direction of aerodynamic stability for load relief control (an Orbiter requirement). Moving the booster nose cones forward to gain volume would shift the center of pressure forward, and locating the oxidizer tank aft of the fuel tank would move the center of gravity aft. Both of these effects will tend to increase the TVC requirements and complicate the intricate interaction between flight control and structural loads.

4.8 LRB Cost Impacts Assessments

Relative cost impacts to the NSTS systems of incorporating various configurations using a variety of propellant combinations, engine packages, and geometries was completed in the first half of the study. Development of cost models and estimates of the cost impacts for flight software, test hardware, and operational spares will be completed and reported in the final report.

Operations cost estimates will also be completed using an Eagle modified version of the KSC Operations Cost Model. The model will provide estimates of a range of traffic models using variable assumptions.

NSTS Liquid Rocket Booster

General Dynamics Corporation

Task III

Guidelines and Requirements To Minimize Space Shuttle System Impacts Summary Report

Prepared By

Eagle Engineering Incorporated

Task III of the STS Liquid Rocket (LRB) study required Eagle Engineering, Inc. to develop design guidelines and requirements to minimize impacts to the Space Shuttle system from an LRB substitution.

Five potential liquid rocket booster configurations were assessed in this phase of the liquid rocket booster study. These configurations consist of one pump fed system using modified existing Space Shuttle Main Engines (SSMEs), one pump fed system using modified existing Saturn F-1 engines, two newly designed pump fed engine concepts using LO2/LH2 or LO2/RP-1 fuels, and one pressure fed system using LO2/RP-1. The following lists the liquid rocket booster concepts:

Configuration	Propellant	Engine
1B	LO2/RP-1	Pressure-Fed
5A	LO2/LH2	Pump-Fed
5D	LO2/RP-1	Pump-Fed
5J	LO2/LH2	NSTS SSME
5K	LO2/RP-1	Saturn F-1

The first four configurations have 4 engines per liquid rocket booster, while configuration 5K has 2 engines per LRB. Each of the liquid rocket booster concepts considered is capable of lifting a 70 Klb payload to 150 n mi orbit. 28.5 degrees inclination with orbiter SSME's limited to 100 percent PL. The boosters must also be capable of lifting a 59 Klb payload to 150 n mi orbit, 28.5 degrees inclination, with orbiter SSME's limited to 104 percent PL. Avionics and power systems were assumed to be common to all concepts.

The design guidelines and requirements to minimize impacts to the Space Shuttle system for these five liquid rocket booster configurations are as follows:

The primary design guidelines and requirements of a liquid rocket booster system reflect the first order selection criteria.

Improved safety is a prime reason for considering liquid rocket boosters as potential solid booster replacements. Liquid rocket boosters should be designed with safety enhancements, such as the capability for intact aborts with one LRB engine out at lift-off, and possible enhanced orbit capability with degradation or loss of a Space Shuttle main engine.

Improved environmental acceptability is another advantage of liquid rocket boosters over solids. Liquid rocket booster designs improve the hazardous near field acid cloud produced by solid boosters. Liquid rocket boosters also prevent the destruction of the ozone layer caused by the combustion of solids.

Other goals of the liquid rocket booster program include Space Transportation System (STS) integration with minimum impact to the STS and launch site. Liquid rocket booster concepts were developed to minimize impacts to the orbiter, external tank, launch site, and ground support equipment.

Liquid rocket booster reliability is also of prime concern. Since the control functions of liquid rocket boosters (e.g., valves, flows, pumps, temperatures, pressures, etc.) are more complex than those of solid rocket boosters, the orbiter pre-launch, pad switch-over and orbiter ascent phase software requirements for monitoring and controlling the LRBs will be more complex. The greater complexity of liquids over solids requires added attention to LRB reliability.

In addition to the basic design rules and guidelines listed above, the following areas must be considered in the development of a liquid rocket booster system:

LRB Maximum Diameter

The maximum liquid rocket booster diameter shall be constrained to prevent increases in wing loading due to aerodynamic flow distortions. The maximum allowable diameter is approximately fifteen feet. See "Liquid Rocket Boosters - Effect of Increased Length and Diameter" in the Special Reports Summaries section for more information.

Flight Load Assessments

A key consideration to potentially upgrading the National Space Transportation System (NSTS), by replacing the solid rocket boosters (SRB's) with liquid rocket boosters (LRB's), is to assure development of an LRB design that is compatible with the NSTS and its associated system design constraints. Accordingly, the effects of LRB thrust, mass property and estimated element aerodynamic characteristics on potentially critical orbiter, external tank (ET) and interface structure were assessed throughout first stage flight for each LRB concept under study. Assessments were performed using a program containing over 80 structural load indicator algorithms that were evaluated using flight simulation trajectory parameters provided by GDSS as inputs. Figure 1 presents two typical load indicators that were evaluated. The straight horizontal lines denote the indicator structural limits while the lines with the triangular symbols correspond to the same limits but with a 90% systems dispersion protection level included. The dotted line depicts the predicted load indicator Mach-history for a particular LRB conceptual design (the RP-1 pressure fed booster in this case). For comparison, the solid Mach-history trace depicts the corresponding load indicator variation that would be predicted for the NSTS using its currently baselined solid rocket booster. As indicated, the "fwd crossbeam thrust panel" indicator shows a significant structural exceedance for the LRB case over a large portion of the trajectory beyond M=2. Similarly, a near-exceedance is seen for the LRB case at M=2.5 for the "crossbeam lower chord fitting" indicator.

Our assessment of the structural load indicators generated for each of the LRB concepts studied revealed that nearly all of the observed structural exceedances were due to excessive LRB thrust in the high Mach number range and that these exceedances could be precluded by appropriate LRB throttling. A recommended LRB throttle logic was developed based on constraining the ET LOX tank aft dome head pressure indicator to its maximum allowable value of 39.2 psi (see Figure 2). This throttle logic concept also can be adapted to protect against other LRB thrust driven load indicator exceedances should further analysis show that the aft dome head pressure indicator does not always represent the most critical load indicator exceedances.

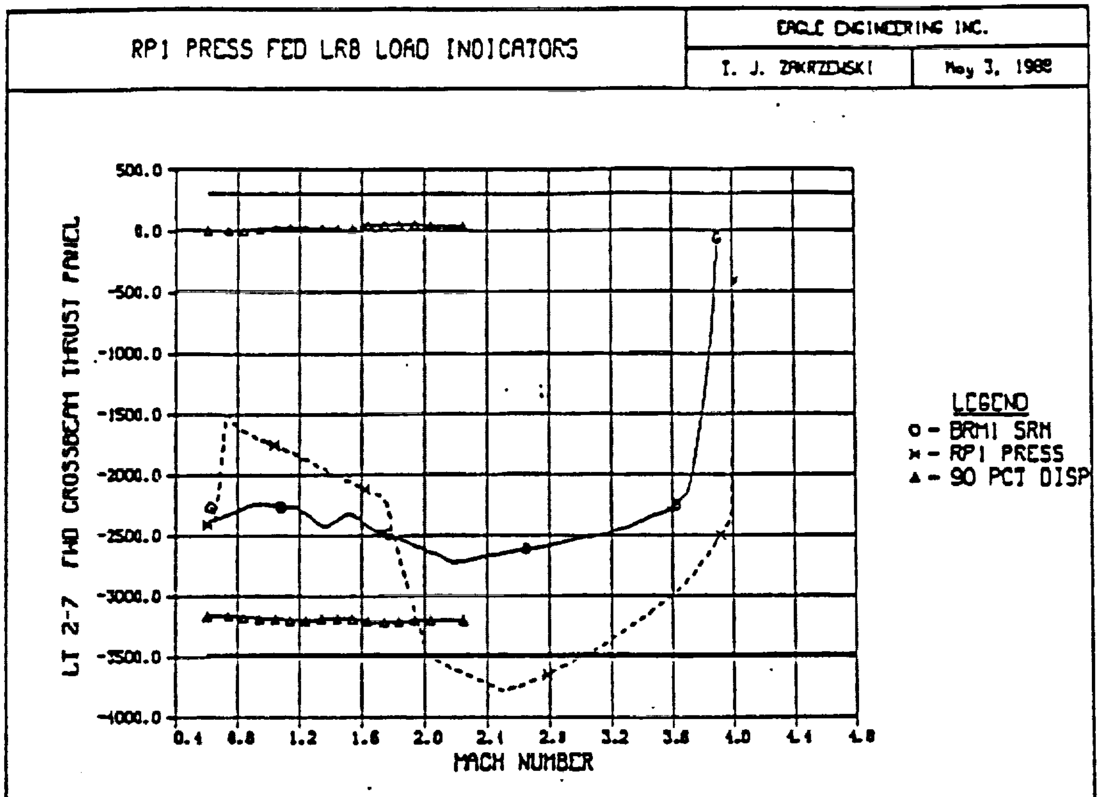


FIGURE 1 (a)

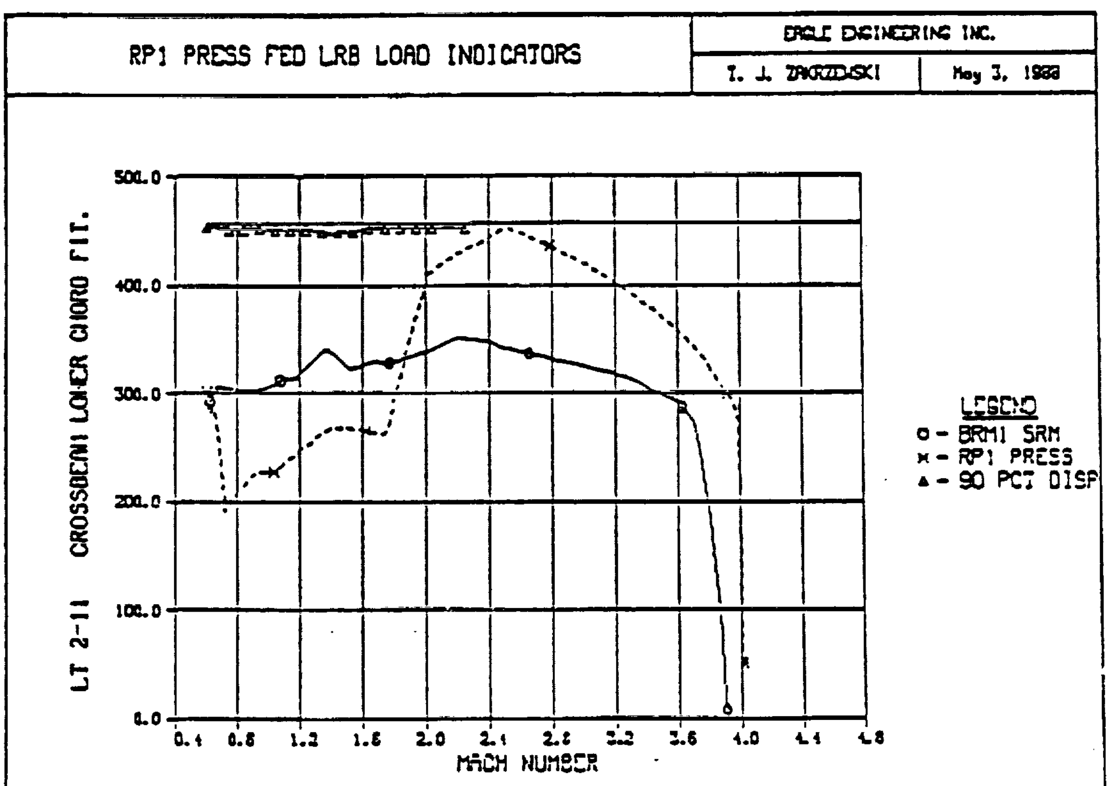


FIGURE 1 (b)

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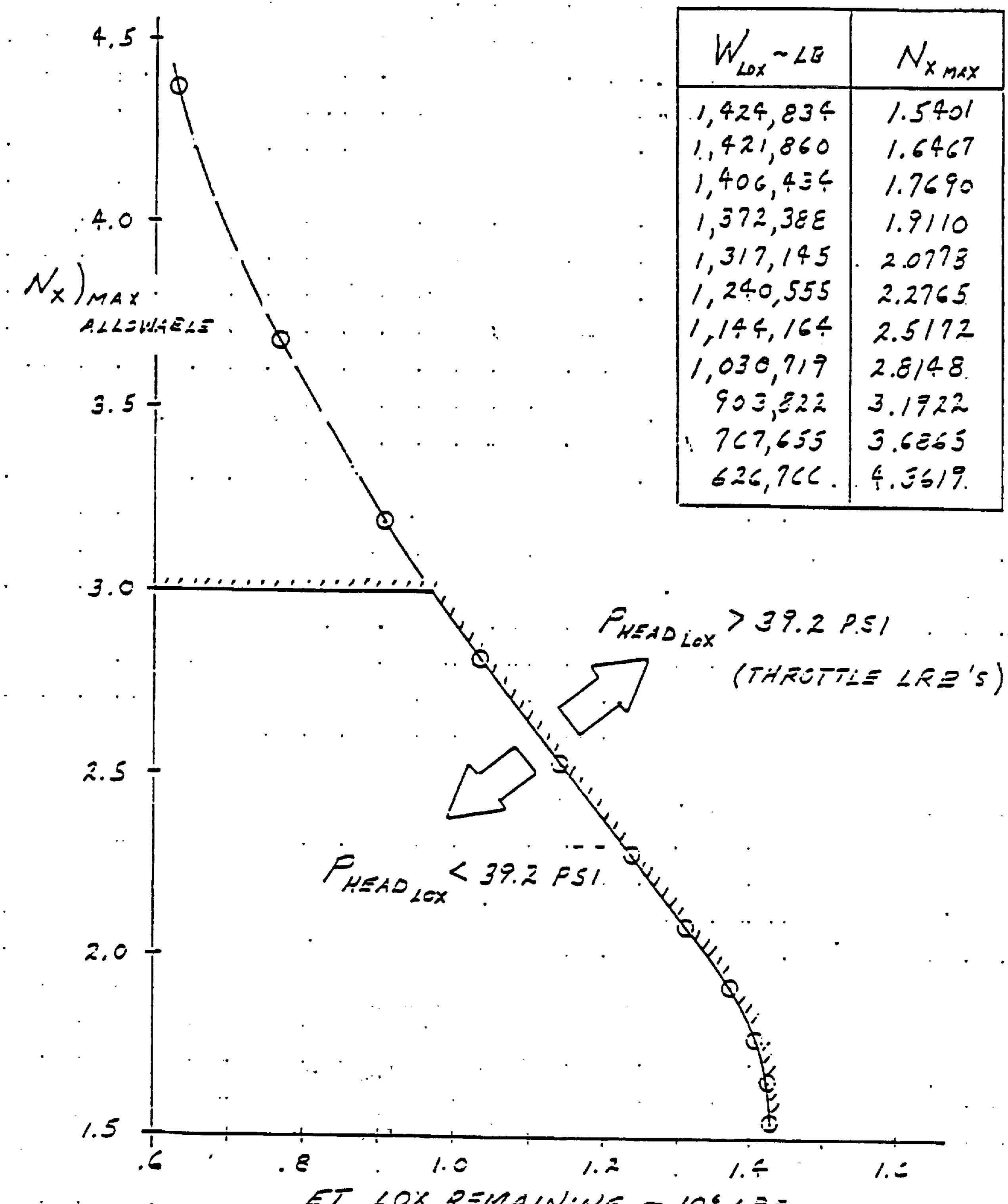
LRB THROTTLE BOUNDARY

ALLOWABLE AXIAL LOAD FACTOR VS ET LOX REMAINING



W_{LOX} ~ LB	$N_{X\ MAX}$
1,424,834	1.5401
1,421,860	1.6467
1,406,434	1.7690
1,372,388	1.9110
1,317,145	2.0773
1,240,555	2.2765
1,144,164	2.5172
1,030,719	2.8148
903,822	3.1722
767,655	3.6865
626,766	4.3619

Figure 2

LRB Estimated Aero Characteristics Assessment

Reasonableness checks were performed on the estimated element aerodynamic characteristics that were used to generate the LRB structural load indicator assessments. While the vast majority of the estimated aerodynamic characteristics appeared to be quite reasonable, several anomalies were observed regarding the increments used to convert the shuttle SRB's to appropriate LRB designs. The anomalies concerned the lateral location of the LRB normal force aerodynamic center and the longitudinal location of the LRB side force aerodynamic center. Subsequently, the element aerodynamic characteristics were revised to correct the observed anomalies. However, due to programmatic priorities, updated trajectory simulations using the revised aerodynamics could not be generated, thus precluding a rigorous reassessment of the load indicators. Upon request, an estimate of the effect of correcting the LRB normal force lateral aerodynamic center was assessed (via hand calculations) relative to the aft ET/LRB interface member loads (struts P8 through P13). Results of the analysis indicated that only the lower horizontal struts, P9 and P12, would be critical and only for the LOX/H2 pump fed concept at $\pm 2.5°$ of sideslip.

Aerothermodynamics

The impacts to the baseline shuttle system, primarily the orbiter and external tank (ET) thermal protection system (TPS) were studied. The shock impingement from the LRB nose onto the higher heating regions of the ET forebody was assessed for its impact on the baseline TPS. The longer LRB's have minimal effect on the orbiter forebody thermal protection system. With the longer LRB's and the forward movement of the shock impingement location, the baseline value of the shock on the intertank is removed. The magnitude of the protuberance effect of the attachment may be lower for the LRB's. Thermal examination of the proposed liquid rocket boosters identified configuration 1b as having the least impact on the external tank thermal protection system, and Configuration 5J as having the largest. The remaining three concepts, 5A, 5D, and 5K, would require a small strip of ablator material to the external tank in order to accommodate their thermal impact.

Plume Heating

An assessment was made of the plume effects on the base region of the Shuttle system. Analysis of the plume environment of the base of the Shuttle reveals little difference among the five configurations. Plume heating is dependent on the number of engines, nozzle area ratio, combustion chamber pressure, nozzle exit location, plume radiation characteristics, and vehicle base pressure. The environments are likely to be reduced for the LO2/LH2 propellants and increased for the LO2/RP-1 propellants. Detailed plume analyses can be computed once engine specifications are defined.

Engine Throttling

All proposed liquid rocket booster configurations will have the capability to throttle the LRB engines. Individual throttling capability would significantly increase the preflight analyses, software, monitoring and controls required. Therefore it is recommended that the engines on each booster throttle as a group.

LRB Data Communications

Data communications for flight control becomes more complex for liquid rocket booster systems because of more engines, various engine out or engine degradation combinations, and possible LRB variable thrust capability. Some of the many considerations include vehicle control, vehicle structural loading capability, variable payload weights, various abort capabilities, etc. The new liquid rocket boosters must be designed to minimize both the hardware and software impacts to the Shuttle integrated avionics while incorporating these capabilities to enhance performance, flexibility, and crew and vehicle safety.

LRB TPS

The external environment surrounding the liquid rocket boosters may result in ice/frost formations similar to those on the external tank. The liquid rocket boosters should be designed in accordance with Shuttle Ice/DETSRIS requirements. This design requirement may affect proposed LRB thermal protection system (TPS) plans, possibly effecting structural response/ design plus non-uniform propellant heating with the potential for inverse propellant thermal stratification.

Acoustic Environment

The acoustic environment generated by the liquid rocket boosters must not exceed that generated by current solid rocket boosters (SRBs). This constraint addresses the sensitivities of payloads and some Shuttle hardware. Acoustic studies must consider the combined effects of Space Shuttle Main Engine and liquid rocket booster interaction.

Liquid rocket boosters will require systems to control acoustic levels prior to lift-off similar to the water spray systems presently used with the solid rocket booster system. The liquid rocket boosters must be designed to accommodate the maximum Shuttle acoustics levels which occur at approximately 80 feet altitude. In-depth tests and analyses will be required on the final configuration.

LRB Separation

The liquid rocket booster system should be designed to allow LRB shutdown and separation from the Orbiter at several times during ascent, as a function of different intact abort scenarios. The analyses and test data relating to separation characteristics of the liquid rocket boosters will define the increased safety margins of the new Shuttle system. See "LRB Separation" in the Special Report Summaries section for more information.

Hydrogen Burn-off

The Space Shuttle Main Engine (SSME) start sequence utilizes a short hydrogen lead which is dumped through the engine nozzle. Accumulation below the engine followed by ignition can cause unacceptable overpressure. This hydrogen must be burned before accumulation occurs. A burn-off system for the liquid rocket boosters is needed similar to that of currently provided for the Space Shuttle Main Engines.

SSME Hydrogen

The new liquid rocket booster design should be prepared to alleviate the problem of unburned hydrogen in the Space Shuttle Main Engines after the oxygen main valve has closed at shut-down. This issue is currently under investigation with the Shuttle using solid boosters. This issue is important since there can be more than 150 pounds of hydrogen per SSME and this unburned hydrogen creates an explosion potential. However, a solution found for the current Shuttle system and associated solid rocket boosters may also apply to a Shuttle using liquid rocket boosters.

LRB Release System

The proposed liquid rocket boosters must be designed with a hold down release mechanism and associated system to assure that all four to eight engines have started and are producing the required thrust. These facts must also be communicated to the orbiter and ground control. This is not required with the present solid rocket boosters.

LRB Purges

The liquid rocket boosters must provide for hydrogen and nitrogen purges of various engine seals and cavities, gas supply to valve actuation systems, and flight pressurant gases. These must be provided while minimizing orbiter interface and impacts.

O2 Geysering Suppression

The liquid rocket boosters shall be designed to suppress oxygen geysering in supply lines. The gas formation in the liquid oxygen system can result in large, highly destructive surges once a significant quantity of liquid is in the line or lines and vehicle. Analyses must be made of these very complex effects for loading, preflight, and flight.

LRB Thrust Mismatch

The liquid rocket booster should be designed to minimize liquid rocket booster thrust mismatch. Equal amounts of thrust should be delivered from each LRB engine for optimum ascent trajectory and to provide even thrust balances between engines during the LRB shutdown sequence. Analysis and testing will be necessary to develop satisfactory operational methods.

NSTS Liquid Rocket Booster

General Dynamics Corporation

Special Report Summaries

Prepared By

Eagle Engineering Incorporated

C-2

LRB Thermal Requirements

Examination of the heating to the Liquid Rocket Booster (LRB) configurations was made in order to determine the type of Thermal Projection System (TPS) required. The LRB heating environments were assessed relative to the Space Shuttle Solid Rocket Booster (SRB) design values and two options for TPS requirements are offered.

A estimate of aerodynamic heating was made by comparing proposed trajectories with a trajectory for which heating rates have been determined. Aerodynamic heating is a function of the square root of atmospheric density and of the velocity cubed. Thus, at the same velocity, one need only to compare altitudes (densities) to obtain the relative values.

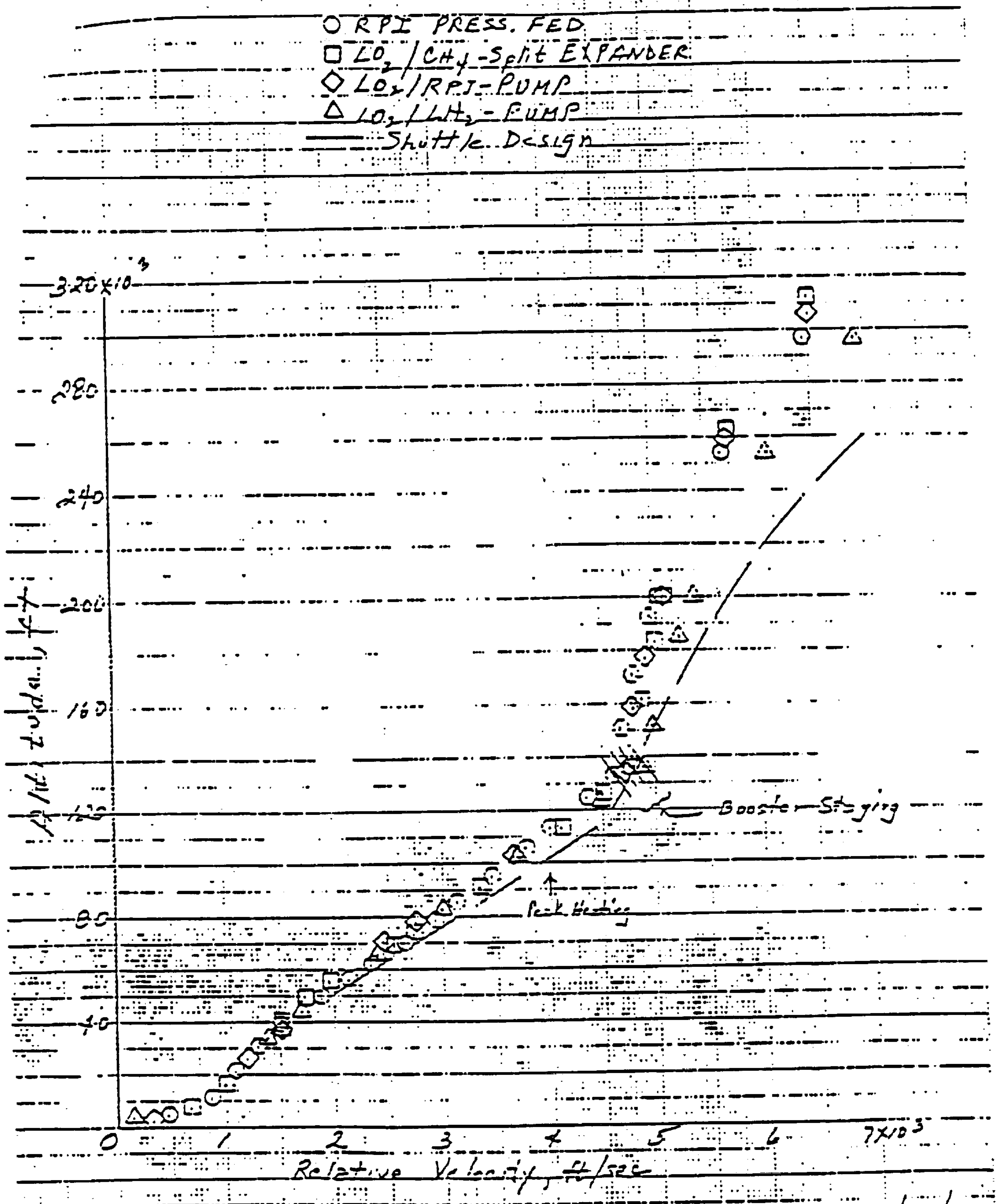
Altitude vs velocity of the proposed LRB trajectories and the aeroheating ascent design trajectory used for the Space Shuttle elements were submitted. All of the trajectories were very similar until approximately 3000 ft/sec velocity when the Shuttle design trajectory begins to deviate. At the time of peak heating, around 4000 ft/sec, the LRB trajectories are approximately 10,000 feet higher in altitude. This means the density is around 60 to 65 percent lower and the heating is 26 to 28 percent lower than the Shuttle SRB. A review of the predicted heating for the SRB revealed that a majority of the maximum heating rate values are 6.0 Btu/ft^2 sec or lower with only a few exceeding 11.0 Btu's (see LRB Thermal Requirements, Figure 1).

Insulation Requirements

Because of the Space Shuttle Program requirement to minimize ice formation on the External Tank (ET) following on-pad propellant loading to avoid ice impact on the Orbiter, a spray-on foam insulation (SOFI) is baselined for the ET. It was found that approximately 1.0 inch thickness of SOFI satisfies the minimum ice requirement. This particular insulation material, identified as CPR-488, has a maximum heating rate capability of 10 to 11 Btu/ft^2 sec and is used as an effective TPS for ascent heating.

In light of the trajectory comparisons, it is recommended that 1.0 inch of SOFI will adequately protect the LRB cylindrical structure and no doubt the aluminum nose for the 2 shorter boosters which are very similar to the SRB. The 2 longer LRBs may require additional TPS on their nose tips since they extend just forward of the ET and may not be enveloped within the ET shock. Cork would suffice for this additional TPS. For those regions of the LRB near feedlines or other protuberances, a Super Light Ablator (SLA) is recommended until the design matures or ground test data become available.

Two options for LRB TPS can be consider at this time; one for protection just past staging and the other to protect the LRB for entry. In the case of a short time flight without the need to survive entry, only SOFI would be required with a little SLA near major protuberances. However, for the LRB to withstand entry heating, cork is recommended on the nose cone and over protruding bolt heads, etc. and SLA near the cowlings and lines.



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Cost Estimation

Eagle Engineering, Inc. support to General Dynamics Liquid Rocket Booster Study included the following cost estimates:

1. Estimates for the impact of mods to the Orbiter, and other STS elements
2. Independent assessment of LRB vehicle costs
3. Estimate of the LRB software development costs
4. Definition of spares program
5. Definition of test program subsystem
6. Operations cost estimates

Cost Impact of Mods to the Orbiter and Other STS Elements

Cost estimates were developed for each of nine LRB configurations depending on several parameters including the complexity of the LRB configuration and the number of engines. The method of estimating was to develop percent changes in the STS systems as a function of the LRB design and then apply these percentages to the original STS element DDT&E.

These estimates identified impacts on the Orbiter Vehicle, primarily in the Avionics systems, impacts to the Flight Software, impacts on the Systems Engineering budgets, the MSFC projects including the External Tank and the MSFC Systems budgets. The total program costs on all STS program elements except KSC were estimated due to the modifications required to substitute an LRB for the Solid Rocket Boosters.

LRB Vehicle Costs

This exercise was conducted in support of the General Dynamics cost estimating team and consisted of EEI developing an independent parametric estimate of each of several LRB configurations based on the LRB subsystem level weight statement and complexity judgments from the EEI engineering staff. The result of this was for the customer to revise certain of his estimates and to develop more rationale in some areas that lacked technical definition. The conclusion that the GDSS Cost Estimating Relationships were comparable in several areas to the EEI CERs. Another result was that the data being supplied by the Engine manufacturers was substantially lower than what the CER estimate of engine development indicated.

Estimate of LRB Software Development Costs

In support of the GDSS cost estimating team, EEI developed an estimate for the Flight Software for the LRB. This estimate was developed based on the size of the LRB computer memory, the number of lines of code required to program the memory and the cost software programming per line of code. The estimate was essentially accepted by the customer and his customer as a reasonable software estimate.

Definition of Spares Program

Another EEI task was the definition of the Spares program and the cost of the program. This task was accomplished by estimating the initial spares requirement the initial spares laying-by reviewing the assumptions regarding vehicle checkout, production rates and availability. Based on these assumptions, and the EEI knowledge of the vehicle assembly and launch sequence, an initial spares requirement was developed which would allow the program to proceed without any delays due to availability of spares. However, not expending large sums of money for components that either would not be spared, such as structure, or would be available from the next vehicle in the production line. In addition, the EEI concept allowed for the time that the vehicle was in the VAB and on the launch pad, and certain elements would have to be replaced in a timely manner. This analysis allowed EEI to develop an initial spares requirement. The second part of this task involved estimating the operational spares requirement once the initial spares laying was established. This was again estimated assuming a "piggy back" spares concept with a probability of sufficiency (POS) of 85 to 90 percent. Once the spares requirement is established, then the cost is estimated based on subsystem and LRU costs.

Definition of Test Program

This EEI task consisted of two elements. First was the estimate by subsystem of the test hardware requirements. These estimates were developed by examining each LRB subsystem such as structure, avionics, TVC and other and making an engineering judgement of what tests were required for those individual subsystems. After developing the test requirements for subsystem development, qualification and certification, EEI converted these into equivalent subsystems and then a cost estimate was developed based on the cost of the individual subsystem. Second, the integrated test program requirements were developed based on developing analogies between the LRB engine programs and the Space Shuttle Main Engine integrated test program conducted at NSTL. For example it was felt that an integrated test program such as the STS Main Propulsion Test Program (MPTA) would be required. This test program was not for the engines alone rather for the total integrated LRB vehicle. In addition, a series of tests were defined based on the EEI technical knowledge of the test requirements.

Operations Cost Estimates

Eagle Engineering had the task to develop the total Operations cost estimates for the LRB program including facilities cost estimates, launch cost estimates and sustaining manpower cost estimates. As part of this task, the KSC launch operations cost model was obtained from KSC personnel and modified to fit the LRB program.

First, the facility requirements were developed based on the study done by the Shuttle Processing Contractor in support of the LRB study. Using the parameters from the KSC launch operations cost model, the price of the new facilities was developed. This estimate was broken into R&D and C of F in order that the customer could differentiate between budgets.

Second, the launch operations costs were estimated, again utilizing the modified KSC launch operations model. This model uses vehicle parameters, mission models, technology and several other parameters to estimate the total launch operations costs. EEI then took this output and separated out costs that would not be chargeable to the LRB program, such as R & PM costs like utilities and security, and developed the EEI estimate of the LRB launch operations costs assuming certain variable costs per launch and certain other costs such as fixed launch operations manpower.

Third, EEI presented this analysis to GDSS showing the total launch operations cost per flight, cost per lb. of payload in orbit and total fixed and variable manpower.

Flight Control Impact of LRB Candidates

The subject comparison has been performed for the Ascent Flight Control discipline. The five configurations examined are identified below. They are:

Pump Fed

Existing Engines:	SSME	1
	F-1	2
New Engines:	LO2/LH2	3
	LO2/RP1	4
Pressure Fed	LO2/RP1	5

The statement of work requested an evaluation of changes required for each, in both the prelaunch and ascent environments. Also, supply supporting rationale, and rank in order of impact. In the Ascent Flight Control System area the major discriminators appear to be as follows:

A. Number of engines

- Number of TVC drivers required (four per actuator X 2 per engine)
- Liftoff T/W with one engine out (impacts tower clearance margins)

B. Length of Booster

- Aerodynamic stability (longer booster moves CP forward)
- Lowest bending mode frequency (longer boosters tend to imply lower frequencies, all else-equal)

C. LOX Tank forward or aft

- Aerodynamic stability
  (LOX Tank forward is a dramatic improvement)
- Stiffness
  (LOX Tank forward requires higher load bearing fuel tank skin -- stiffer)

D. Pressure fed or pump - Pressure fed requires thick tank walls -- stiffer

The above categorization of discriminators are in the obvious differences between the configurations. Notice that they all are evaluated by a different set of discriminators, these being:

A. Avionics impact (#TVC servo valve driver amplifiers)

B. Liftoff T/W with engine out

C. Degree of Aerodynamic Stability

D. Lowest First Bending mode frequency

Let us eliminate the first two from this list, since they provide absolutely no discrimination between four of the five configurations and have offsetting virtues for the remaining configuration (F-1 engines). This leaves only two major discriminators for the evaluation.

Before doing the actual evaluation, which is the latter part of the task, we address the first part, i.e. changes required for pre-launch and ascent phases. In the prelaunch phase there would be changes to the gimbal test program and its pertinent "Launch Commit Criteria". In the ascent phase there would be changes in FCS filter coefficients, loop gains, trim profiles, discreets, and guidance tables. For the most part this would entail changes of existing software parameters (all of which are not "I-Load") with very little actual software structure changes. There is an avionics hardware impact for addition of more ATVC Driver Amplifier Boxes. This impact is substantial, but it is not an important configuration discriminator.

Evaluation

Evaluation Discriminators

- Degree of Aerodynamic Stability (AS)
- First Bending Mode Frequency (BF)

Parameters

- Booster Length and Diameter
- LOX Fwd/Aft
- Pump/Pressure Feed

Procedure

1. From drawings obtain lengths of the five candidates and location of LOX tanks.
2. Using the "View from Afar" (SWAG) technique visualize changes away from the reference configuration (STS with SRB's) on mass distribution, stiffness, center of pressure, and center of gravity.
3. Rank each configuration for each discriminator, where rank 1 -- 5 implies best to worst.

Groundrules and Assumptions

1. Tank length parameter is more influential on the two discriminators than tank diameters.
2. Booster mass centers for the reference configuration are near the composite mass center.

3. Redistributing booster mass away from composite mass center will lower first bending mode frequency.

4. LOX tank forward or aft will have similar impact on BF in detailing away from the reference, for the <u>same tank length</u>.

5. Longer tank implies lower BF, but more so for LOX tank forward than for LOX tank aft.

6. LOX tank forward has stiffer fuel tank implying higher BF.

7. Pressure-fed configuration (#5) has thicker tank walls and hence will have highest BF.

8. For LOX tank forward a length increase moves the C.G. forward faster than the C.P., hence <u>longer is better</u> in this case.

9. For LOX tank aft a length increase moves the C.P. forward faster than the C.G., hence <u>longer is worse</u> for this case.

Discriminator Ranking

The above "Partial Derivatives" are now manipulated in Table 1 below to arrive at separate rankings for each discriminator.

Table 1 - Parameters and Sensitives

Config	Description	l (Ft)	LOX Pos	AS(Rank)	BF(Rank)	FCS(Rank)
1	SSME	193	Fwd	1	3	1
2	F-1	172	Aft	4	5	5
3	NE LO_2/LH_2	188	Fwd	2	2	2
4	NE LO_2/RP-1	163	Aft	3	4	4
5	PF LO_2/RP-1	175	Aft	5	1	3

Rationale

The discriminator rankings in Table 1 are determined via the following lines of reasoning:

Aerodynamic Stability (AS)

1. More is better

2. LOX FWD superior over LOX AFT for all other combinations of parameters

3. Configurations 1 & 3 have LOX forward

4. Assumption #8 states that longer is better implying that configuration 1 ranks first and 3 ranks second

5. Of the remaining three configurations tank length is the discriminator as per assumption #9, yielding:

Rank	Config.
3	4
4	2
5	5

First Bending Mode Frequency (BF)

1. Higher is better

2. From assumptions #5 and #7 we conclude that configuration 5 ranks first.

3. Configurations with LOX fwd (1&3) also have longer length, implying lower BF according to assumption #5. This is offset by assumption #6 (stiffer fuel tank walls) when commparing these two configurations with the remaining configurations (2 & 4).

4. Presuming the impact of assumption #6 is greater than that of assumption #5, we rank configurations 1 & 3 above 2 & 4, and use relative length as the tiebreaker, yielding.

Rank	Config.
2	3
3	1
4	4
5	2

Ascent Flight Control Impact

As would be expected ranking order does not coincide for the two discriminators. Since there is no "absolute" quantitative data the direct application of weighing factors is not deemed appropriate. However, with some subjective reasoning and weighing the order shown in the final column of Table 1, above, was chosen.

Lift-off Transient Investigation

General Dynamics' "Liquid Booster Study, Volume 1, Executive Summary" states that substantial factors work needs to be done on the lift-off release system. This investigation was indicated with the goal of combining a post step impact with a partial rank impact to see how far up the "thrust curve" an explosive release system can be delayed beyond T/W = 1 before limit load of "Booster/ET" thrust fittings are exceeded. It is a trade-off between current SRB practice if "step thrust rise slope" with no delay, compared with "much shallowed thrust rise slope" with some delay. The objective is to see if we can allow the booster engines to attain somewhere near 90% thrust level before explosive release of Shuttle from the pad. There may be some advantages in staying with the current shuttle explosive release system rather than "changing out" to a "slow release" (extended metal) system.

After some preliminary analysis, a computation was made for launch pad release at 87% full thrust level. This resulted in loads very slightly exceeding (1.2%) the design limit loads of the thrust fittings. An 86% level of thrust at release would undoubtedly result in loading with in the design limit loads of the fittings.

If the performance of the engines can be assessed by the time the engines reach the "mid-80" percent level, then explosive (sudden) release from the launch pad appears to be satisfactory.

Time ran out to develop transfer function and resulting of the "skin-stringer" design. Response was generated for the monocoque design only.

Study Description

The GD LO2/LH2 18 ft. diameter liquid booster was examined both the "monocoque" version and the "skin-stringer" version. The monocoque version was found to have the same frequency characteristics as the present SRB Shuttle configuration, i.e. 19 Hz longitudinal frequency for the pair of booster and 4 Hz longitudinal frequency for the lumped "orbiter/ET" mass. The "skin-stringer" design has frequencies of 14 Hz/3 Hz, respectively.

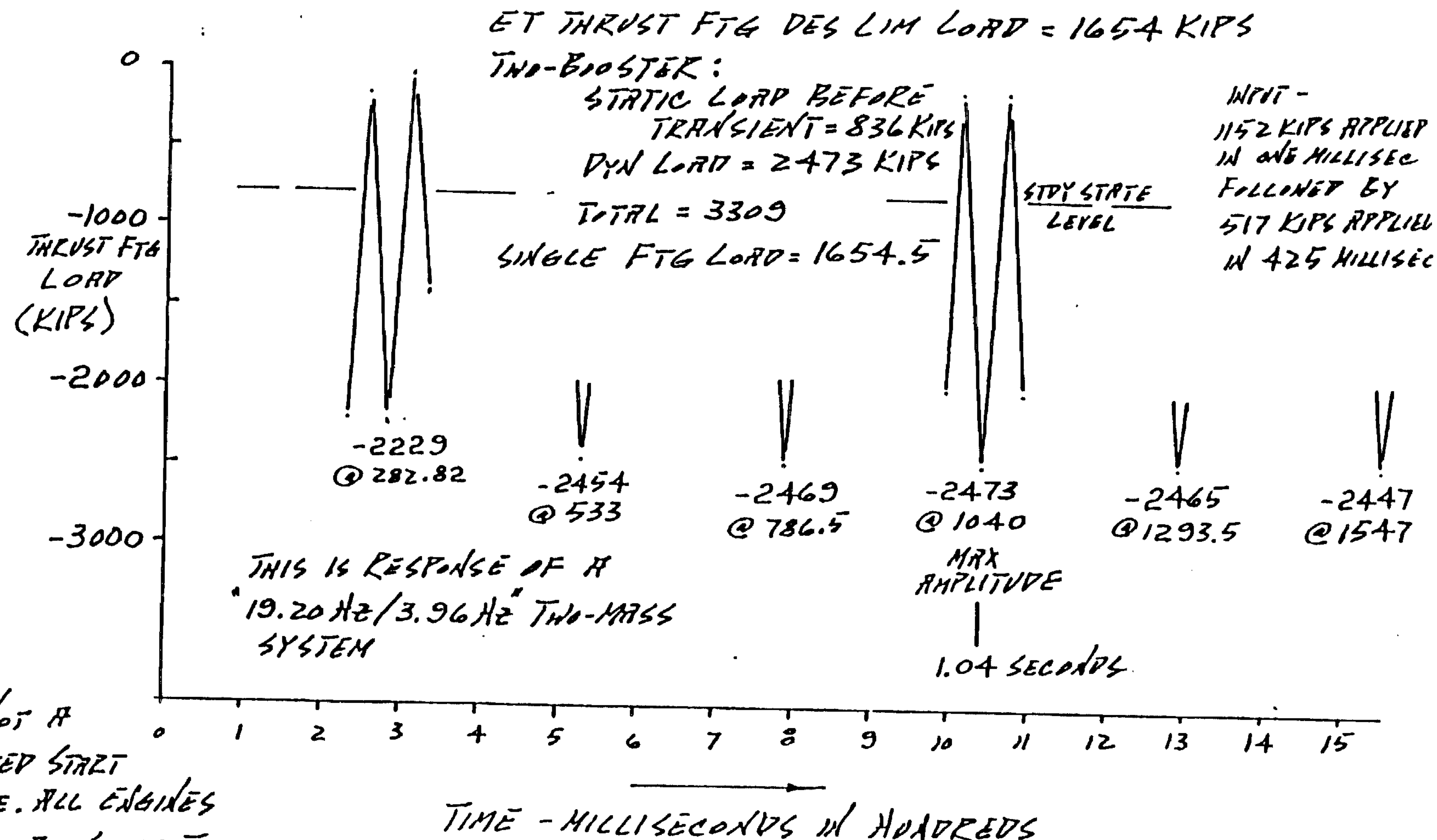
Figure 1 are the computations of weights, load levels and stiffnesses of the boosters. Figure 2 is examination of these load levels with thrust rise slope and roll over of the "helium spin" engines (page 5-12, GD Volume II final report). Examination of vehicle configuration, led to the inputs for frequency determination.

Figure 4 is the same type data for the current SRB Shuttle configuration for comparison. Since the monocoque version of the GD LRB had the same frequencies as the SRB, the SRB transfer function was used (figure 5). The response nature of this transfer function has been previously given to General Dynamics. It is shown as figure 6 here, with the magnitude points "V", "W", "X", "Y", and "Z" labeled. These are the points around the high load point "X". This plot (figure 6) is the average of the first five shuttle flights.

The five labeled points were investigated for "step" input, and are plotted on figure 7. Looking back to figure 2 and the computation on figure 7, it is seen that about 78% of thrust level is all that can be tolerated and not exceed ET thrust fitting (and back-up structure) design limit load.

GENERAL DYNAMICS LO_2/LH_2 MONOCOQUE PUMP-FED BOOSTERS

LIFT-OFF TRANSIENT WITH RELEASE FROM LAUNCH PAD DELAYED TO 87% FULL THRUST LEVEL



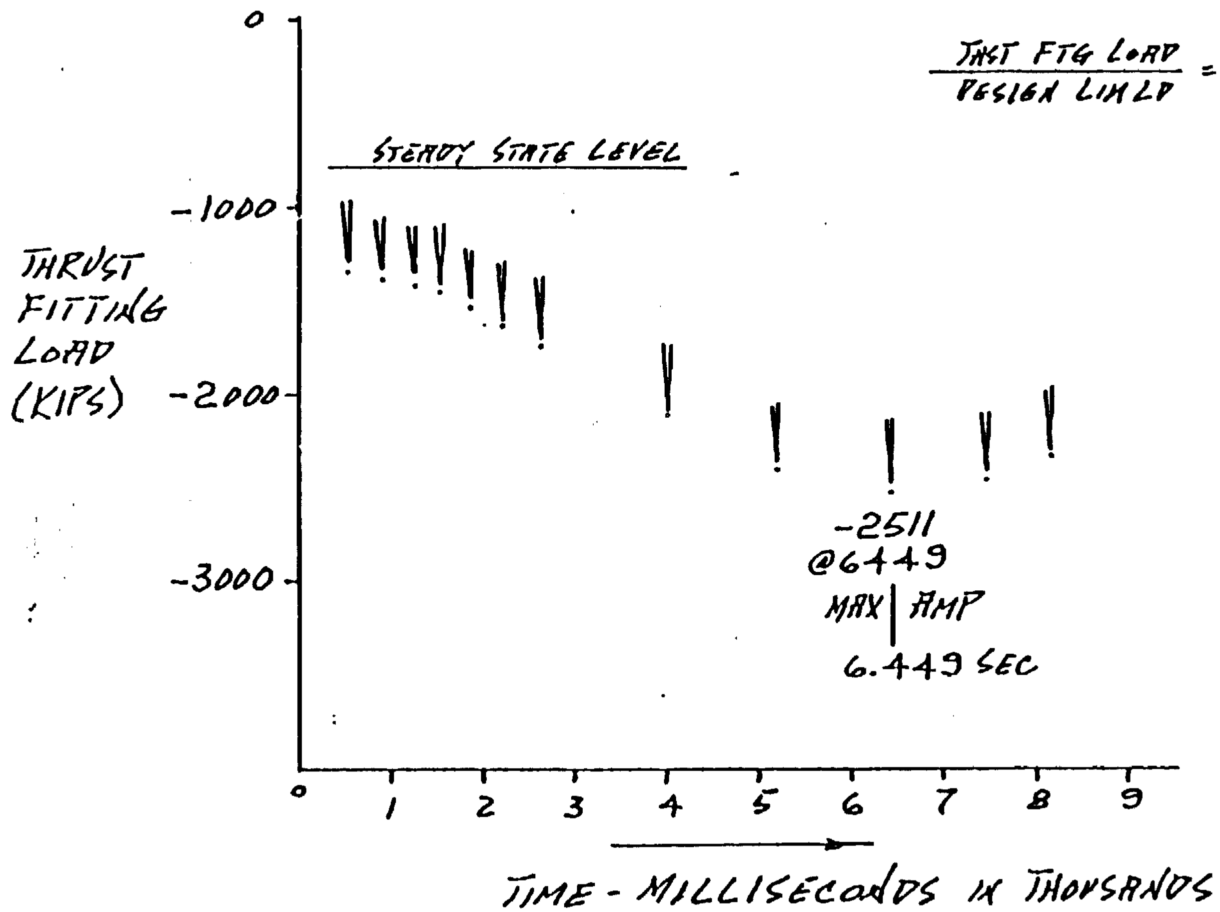
NOTE -
THIS IS NOT A STAGGERED START RESPONSE. ALL ENGINES STARTED AT SAME TIME

WILL HOYLER
12-2-88

GENERAL DYNAMICS LO_2/LH_2 "SKIN-STRINGER"
PUMP-FED BOOSTERS

LIFT-OFF TRANSIENT WITH RELEASE FROM LAUNCH
PAD DELAYED TO 87% FULL THRUST LEVEL

$$\frac{\text{THST FTG LOAD}}{\text{DESIGN LIM LD}} = \frac{2511+836}{1634*2} = \frac{3347}{3268} = 1.024$$



THIS IS RESPONSE OF A
"13.97Hz/2.87Hz"
TWO-MASS SYSTEM
INPUT WITH A 1152 KIP
STEP INPUT OF ONE MILLISEC
FOLLOWED BY A 517 KIP
RAMP INPUT OF 425 MILLISEC.

WILL HOYLER
12-2-88

TRANSFER FN FOR
GP LO_2/LH_2 "MONOCOQUE"
BOOSTER (19.20Hz/3.96Hz)

2.4126^{-3} $\overline{|}\,6.031858^{6}$ $\overline{|}^{2}$ $\omega = 24.881414$
$\zeta = .00001$
$\alpha = -2.4881414^{-4}$ ← M_1
$\beta = 24.881414$

1.200649^{-6} $\overline{|}\,6.031858^{6}$ $\overline{|}\,1.244071^{6}$ ← M

$s^4 + 3.52303^{-3}s^3 + 15934.602s^2 + 8.73585s' + 9.009741^{6}$

$\overline{|}^{2}$ $s^2 + 3.07133337^{-3}s + 15347.60076$

3.85602 Hz
$t = .259335$

$\omega = 24.22809866$
$\zeta = 9.32178228^{-6}$
$\alpha = -2.2584907^{-4}$
$\beta = 24.22809866$
$a = 4.51698^{-4}$
$b = 587.0007648$

$\overline{|}^{2}$ $\omega = 123.885434$
$\zeta = 1.2395862^{-5}$
$\alpha = 1.535666686^{-3}$
$\beta = 123.885434$

19.716979 Hz
$t = .0507177$

$\left(\frac{.259335}{.0507177}\right) = 5.1133$

$\omega_1 = 19.20\,Hz = 120.63716$ R/s
$\omega_2 = 3.96\,Hz = 24.881414$ R/s
$\zeta_1 = \zeta_2 = .00001$
$\frac{m_2}{m_1} = 1944/1579 = 1.23116$
$\bar{A} = .00034$
$B = 619.085$

WILL HOYLER
11-30-88

TRANSFER FN FOR
GO LO_2/LH_2 "SKIN-STRINGER"
BOOSTER (13.97 Hz/2.87 Hz)

1.7553^{-3} $\overline{T}_{4.3888}^{6}$ $\overline{T}^{2}$ $\omega = 18.03274$, $\zeta = .00001$, $\alpha = 1.8033^{-4}$, ~~$\beta = 18.03274$~~ ← M_1

6.33137^{-7} $\overline{T}_{4.3888}^{6}$ $\overline{T}\,9.01637^{5}$ ← M_2

$$s^4 + 2.5602^{-3} s^3 + 8430.1717 s^2 + 3.3496 s + 2.505393^{6}$$

2.7951 Hz $\overline{T}^{2}$ ~~$\omega = 17.56229$~~
$\frac{1}{z} = .357766$ $\zeta = 9.32487^{-6}$
$\alpha = 1.63766^{-4}$
~~$\beta = 17.56229$~~
~~$a = 3.2753^{-4}$~~
$b = 308.4339$

~~$s^2 + 2.232068^{-3} s + 8421.7378$~~

$\overline{T}^{2}$ $\omega = 90.12068$~~2467~~   14.343
~~$\zeta = 1.23871^{-5}$~~ $\frac{1}{z} = .069$
$\alpha = 1.116334^{-3}$
$\beta = 90.12068$~~466~~

$\frac{.357766}{.06972} = 5.1315$

352
70

$\omega_1 = 13.97\,Hz = 87.7761\ r/s$

$\omega_2 = 2.87\,Hz = 18.03274\ r/s$

$\zeta_1 = \zeta_2 = .00001$

$\frac{M_2}{M_1} = 1944/1579 = 1.23116$

$A = 2\zeta\omega = .00$~~3607~~ $.0002800$

$B = -\omega^2 = -325.17971$

WILL HOYLER
11-30-88

LRB Effect on Shuttle Heating

The effects on the Space Shuttle elements of replacing the Solid Rocket Booster, SRB, with Liquid Rocket Boosters, LRB, has been investigated for the aerodynamics heating impact. The various options offered by General Dynamics Space Division were reviewed as to the effect of the different lengths of the LRB's on the ET forebody and the Orbiter base regions.

External Tank (ET) Forebody

An assessment of the heating impact was made by comparing the proposed heating with the baseline design values. Figure 1 shows a distribution of the maximum heating rates that are used for the baseline ET TPS on the ET ogive and intertank regions. (Figure 2 identifies these regions). The magnitude of the heating rates dictate the type of TPS. Because an inch of insulation material, SOFI, is required to insulate the tank from ice formation while the vehicle is on the pad, it was decided to also use the SOFI as the TPS. Characteristics of this material are such that at heating rates above 8 to 10 Btu/ft^2-sec, SOFI is assumed to have ablated off of the structure. Therefore, at higher heating rates, Super Light Ablator (SLA) is used which can withstand heating rates up to 30 Btu/ft^2-sec. Figure 3 illustrates the ET TPS.

Examination of Figure 1 shows two regions of high heating on the forward ET. The heating near X/L of 0 is a result of the shock from the 30°/10° conical tip onto the ogive and the heating on the intertank is the result of two influences. The first is from the shock off of the SRB which impinges on the ET between an X/L of 0.28 to 0.30. The second is due to protuberance heating around the ET/SRB attach point at X/L of 0.357. On the intertank, the high heating can be accommodated with the massive intertank structure. Note on Figure 1 that the tip of the SRB is opposite the ET X/L of 0.225 and the shock impinges a delta distance downstream of 0.055 to 0.075 which corresponds to a distance of 8.5 to 11.5 feet. The shock impingement increases the heating by a factor of four whereas the shock off of the ET tip onto the forward ogive is a factor of approximately two. In an effort to illustrate the impact of a longer LRb whose nose is forward of the baseline SRB, the design heating values have been increased by a factor of four. In order to not exceed the allowable 30 Btu/ft^2-sec for SLA, (whose interface occurs at X/L of 0.04) the forward movement curve suggests that the LRB nose tip should not be more than 1.5 to 5.4 feet ahead of the ET. This assumes that the shock impingement is still 8.5 to 11.5 feet aft of the LRB nose tip. There are ablators with higher heating rate capability such as MA-25S which is heavier than SLA but can take heating rates up to 75 Btu/ft^2-sec.

Orbiter Base Regions

There are many variables associated with the prediction of plume radiative heating rates. Factors such as chamber pressure, nozzle exit area, type of fuel and oxidizer, turbulent exhaust afterburn and view factor are required to be known in order to determine the plume shape and the radiative environment. Using the Shuttle predictions as a calibration and consulting with several experts, it was decided that the LRB's would produce less radiation than the SRB's with some estimates as much as 50 percent less. For this study, it is recommended that 30 percent less radiation be assumed.

Examination of Option 9 with the three vertical nozzles, reveals that the LRB nozzle is approximately 5 feet closer to the Orbiter body flap trailing edge than the baseline SRB nozzle; that is, 15 feet as opposed to 20 feet, based on scaling option 9 and option 1 drawings with the simplifying assumption that radiation is a function of the distance squared, option 9 would produce approximately 56 percent higher heating than option 1. However, the resultant effect is only a 9 percent increase to the Orbiter Body flap trailing edge baseline. This is illustrated in Figure 4 which shows the predicted heating rate to the trailing edge for the baseline and for the LRB's. The curve labeled "SRB Radiation" is the current design value for the SRB radiative heating component of the total heating to the body flap. (The SSME + SRB Radiation is the total.) The bottom long-dash curve is the assumed 30 percent reduced radiative heating of the LRB plume to the trailing edge and the "option 9 LRB" curve is the 56 percent increase to the LRB radiation. Because the LRB's would lack liner material and residual solid propellant particles, they would not exhibit the high shutdown spike that the SRB's produce at separation.

The option 9 drawing suggests that the nozzles are touching each other. If they are to be gimballed and are spaced, then the upper nozzle would be nearer to the Orbiter with a resultant higher radiative heating to the trailing edge. The present maximum heating rate shown of the total SSME plus option 9 LRB is around 25 Btu/ft^2-sec. This corresponds to a radiation equilibrium temperature of 2350°F. While the current TPS on the trailing edge can take 2300°F for 100 reuses and around 2600°F for one use, it is recommended that the option 9 study be judicious in establishing its proximity to the body flap.

Distribution of Maximum Design Heating Rates on ET

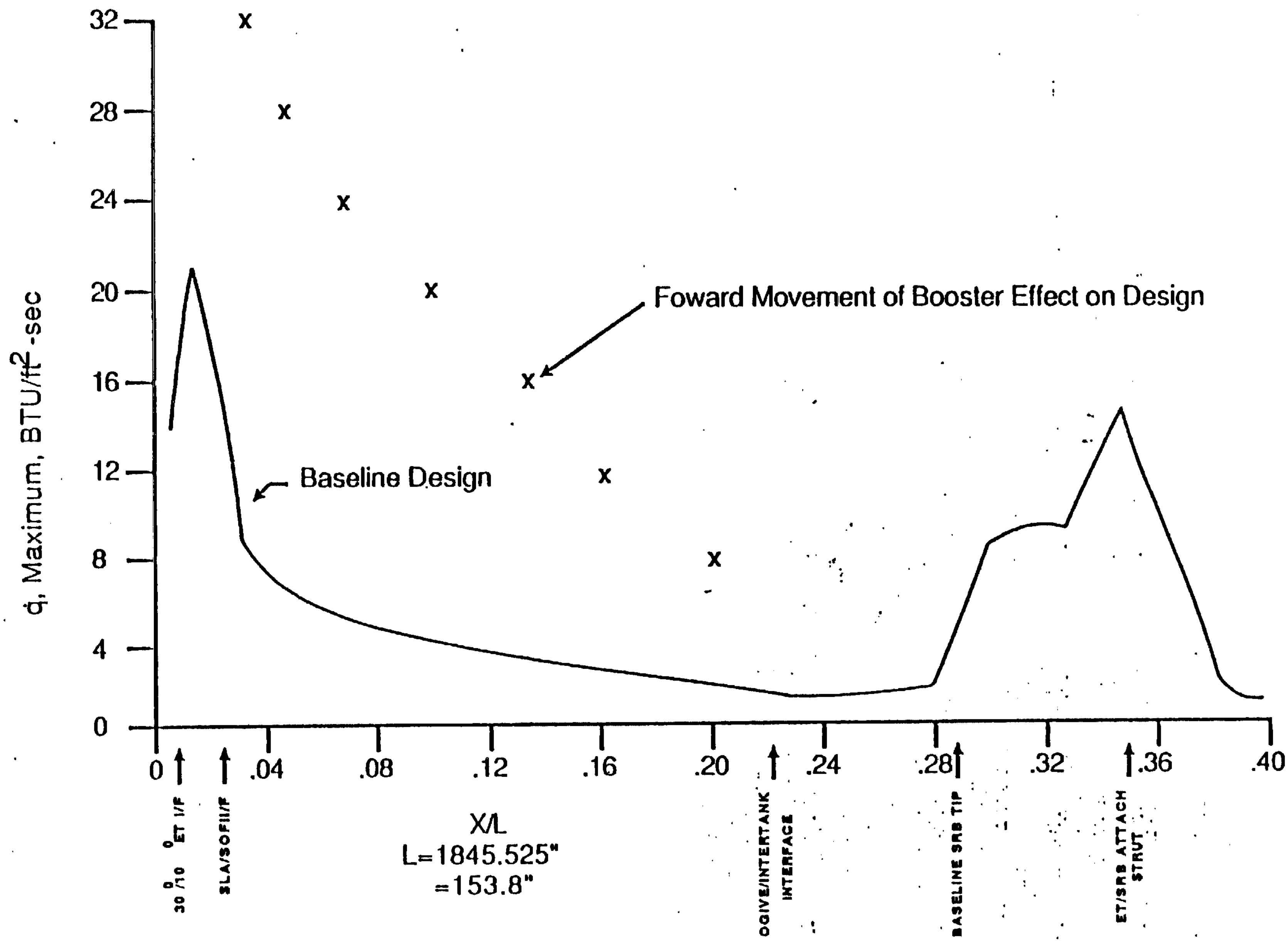


FIGURE 1

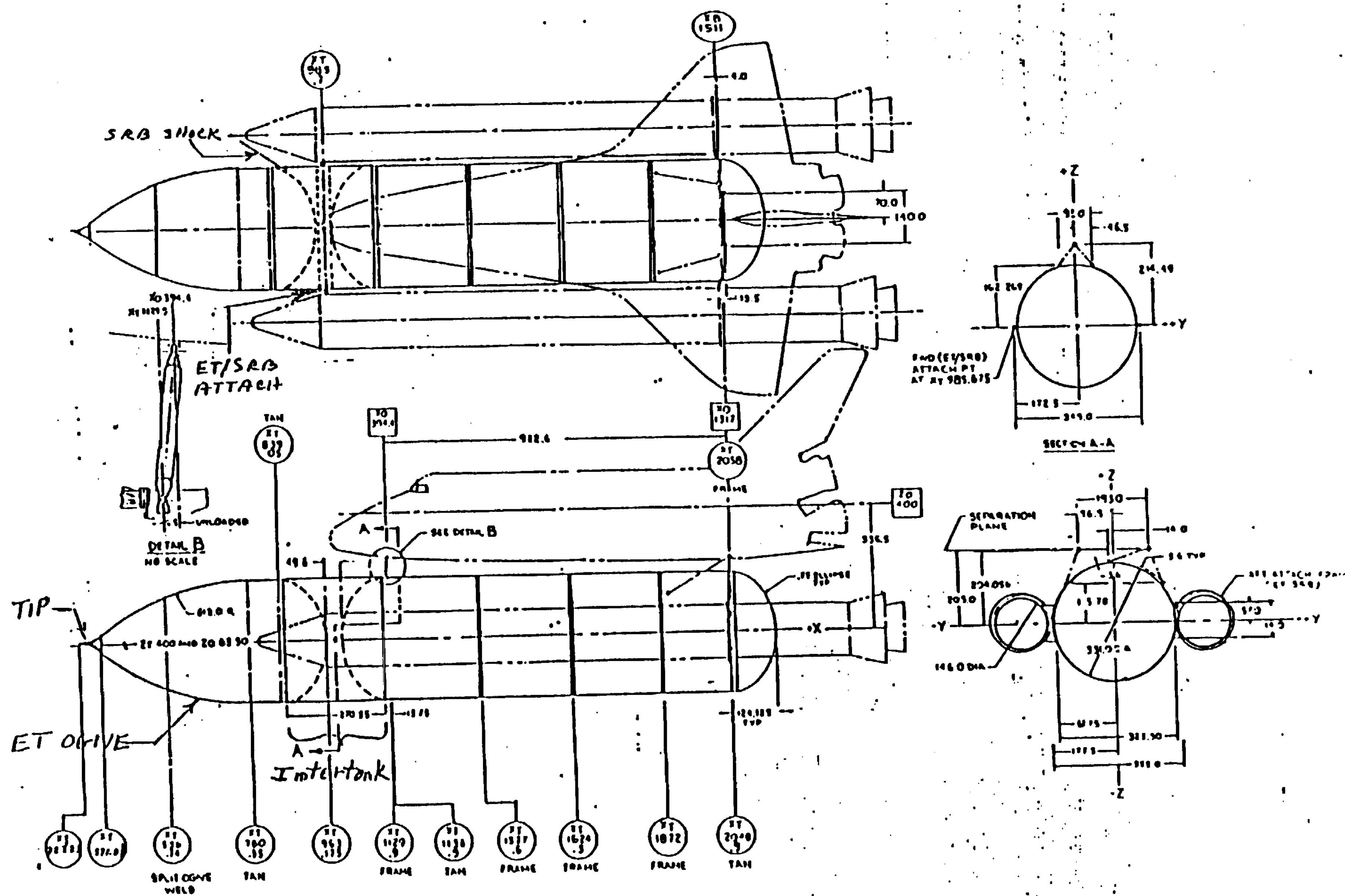


FIGURE 2 SHUTTLE SYSTEM LAUNCH CONFIGURATION

FIGURE 2

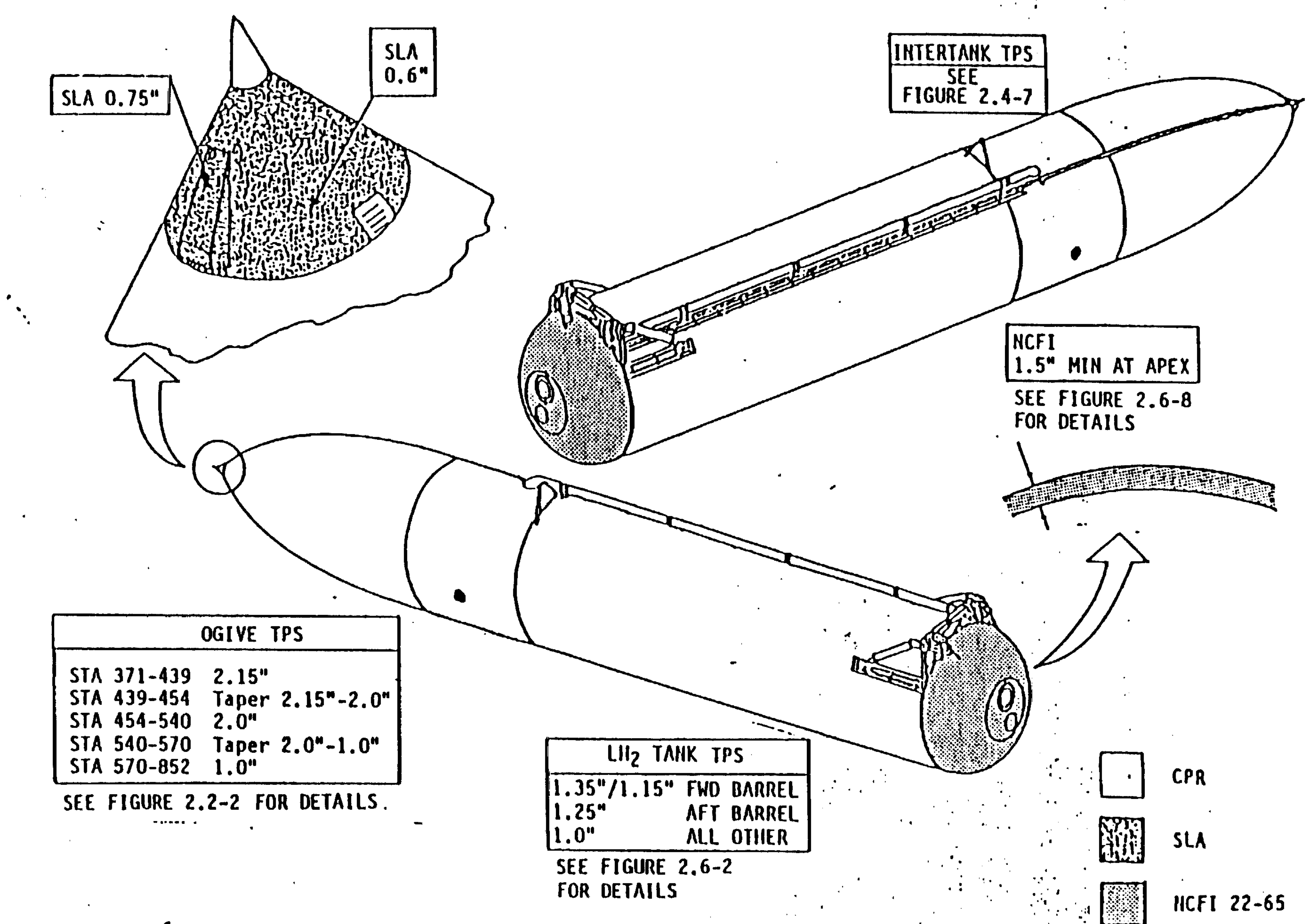


FIGURE 3.0: ET TPS CONFIGURATION OVERVIEW (LWT 44 & UP)

FIGURE 3

Design Plume Heating Rates to Orbiter Body Flap Trailing Edge

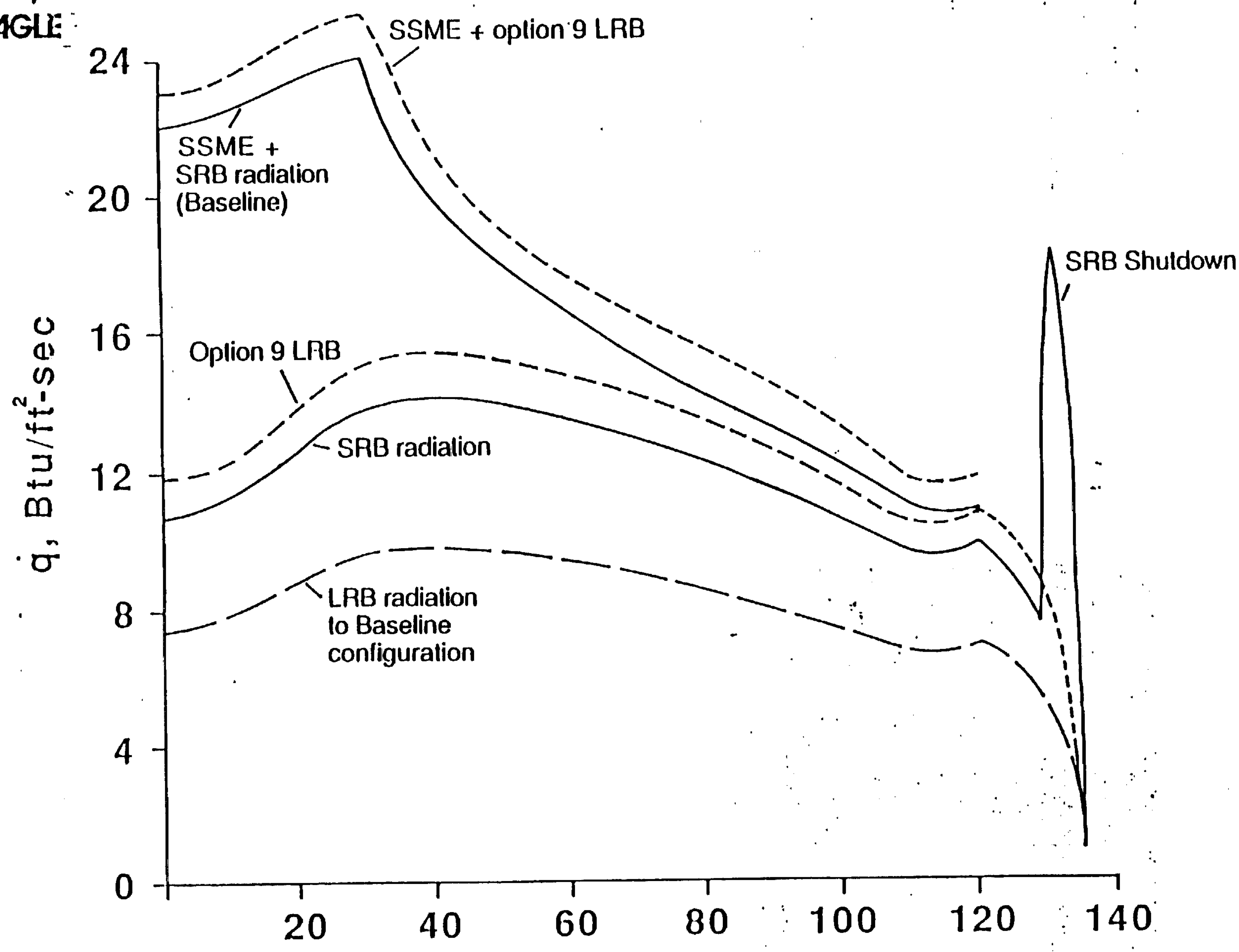


FIGURE 4

LRB Separation

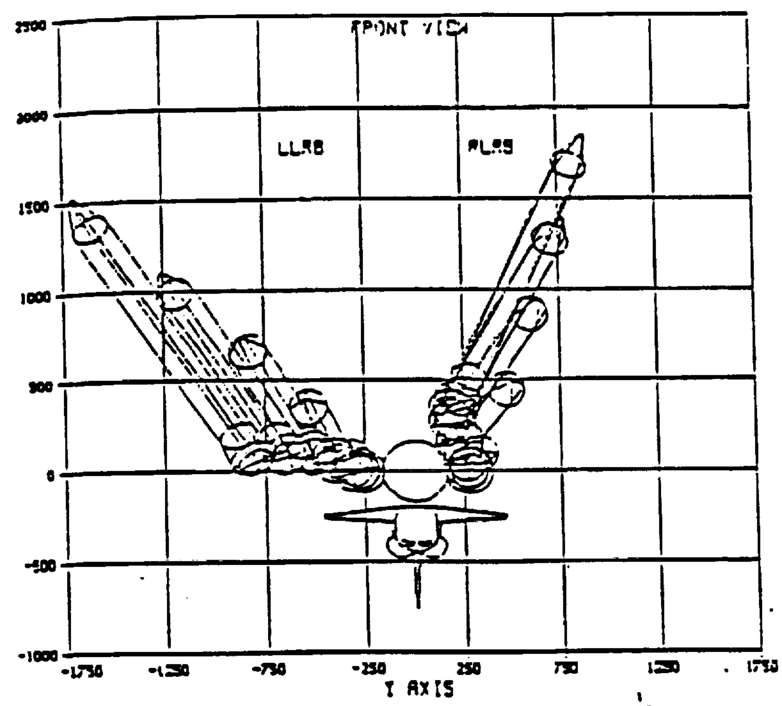
A preliminary analysis of LRB Separation was performed to evaluate their impact on the separation system. The conditions that were examined consisted of nominal separation along with aborts at 100 and 75 seconds. Four LRB configurations were examined. They were LOX/LH2, LOX/RP1 pressure fed, LOX/RP1 pump fed, and LOX/CH4. In general, the nominal separation conditions did not pose a problem for any of the LRB configurations. An off-nominal case was run for all of the configurations. The conditions for this case were as follows:

Alpha=Beta= 10 degrees, roll, pitch, yaw rate = 5,2,2 degrees/sec.

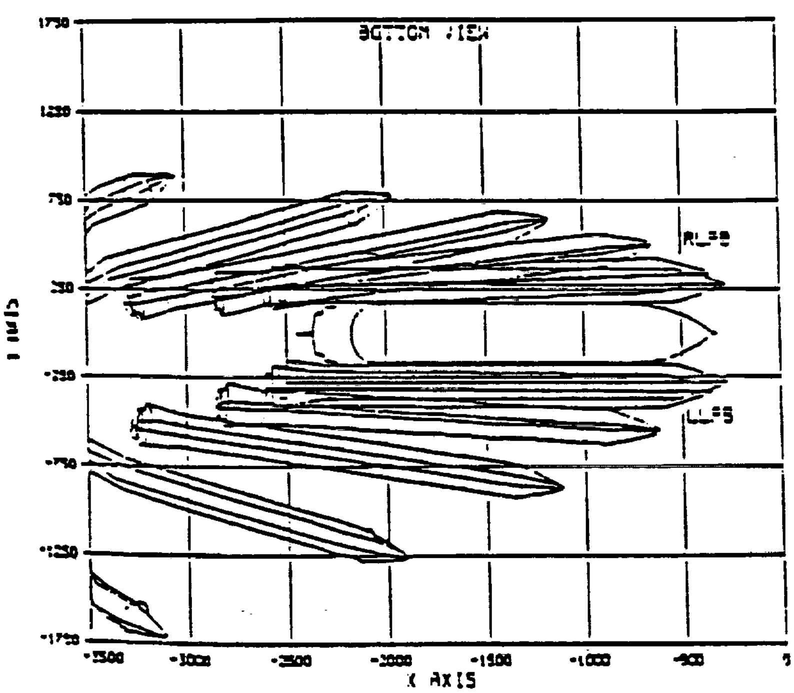
A pictorial presentation of the LOX/LH2 booster separation for the above conditions is presented in Figure xx. The LOX/RP1 pressure fed booster was the only one that had a problem with this design point. Due to the heavier weight of the pressure fed booster and the location of its center of gravity, it required additional thrust for a clean separation.

Only the LOX/LH2 configuration was studied for the abort conditions. There are several problems that affect abort separations. They are the increased weight of the vehicle, the center of gravity is farther forward, and the dynamic pressure is considerably larger than normal. These problems tend to make separation difficult for aborts. Compounding the problem is the fact that the proximity aerodynamic flowfield for the boosters is completely different from the nominal separation environment. For an abort at 100 seconds the thrust on the booster separation motors would have to be increased approximately 25 to 50%. At 75 seconds the center of gravity is so far forward that it is difficult to rotate the LRB nose away from the External Tank. It was found that the forward thrust would have to be increased by 100 to 150% to have any chance at a successful separation.

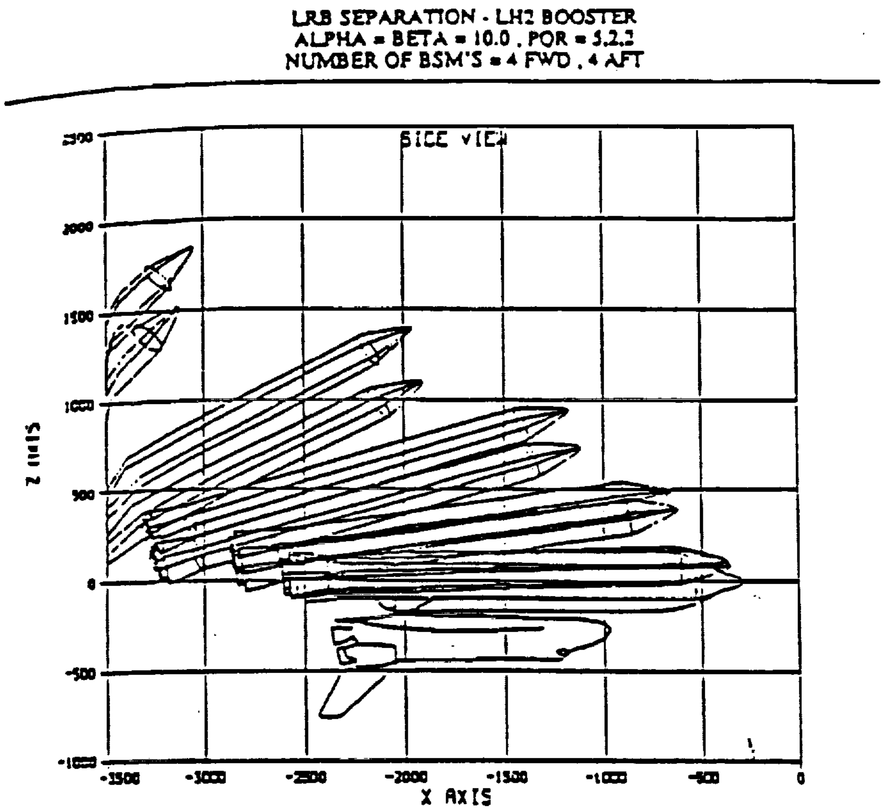
LRB SEPARATION - LH2 BOOSTER
ALPHA = BETA = 10.0 , PQR = 5.2.2
NUMBER OF BSM'S = 4 FWD , 4 AFT



LOX/LH2 Pump-fed Nominal Ascent (Design Case) Separation, Front View



LOX/LH2 Pump-fed Nominal Ascent (Design Case) Separation, Bottom View



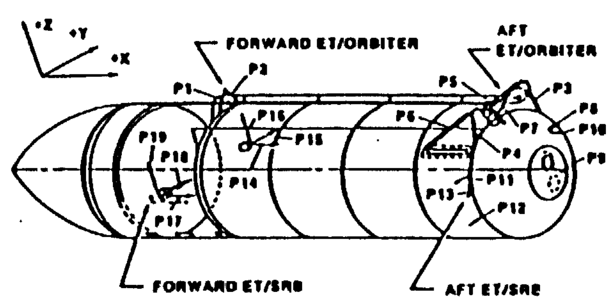
LOX/LH2 Pump-fed Nominal Ascent (Design Case) Separation, Side View

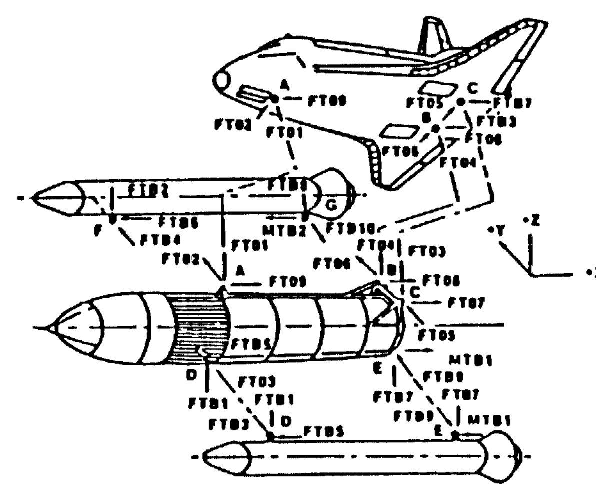
Liquid Rocket Boosters Effect of Increased Length and Diameter

Studies were made of possible Liquid Rocket Booster lengths and diameters to identify constraints which would prevent increases in wing loading due to aerodynamic flow distortions. The following charts show the findings of these studies.

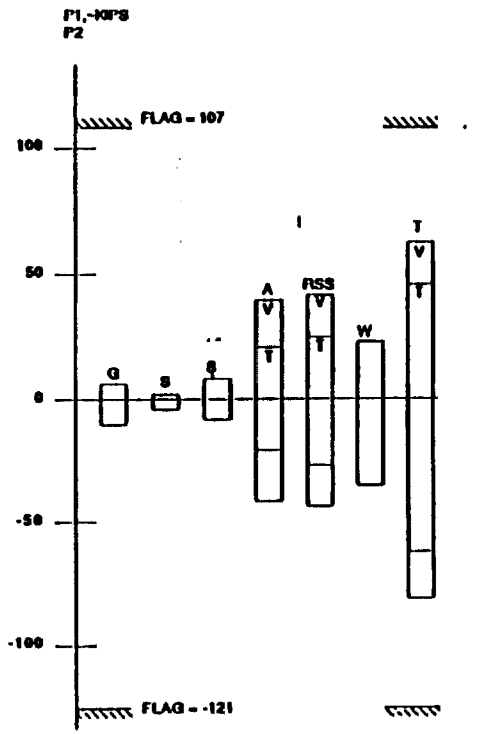
LIQUID ROCKET BOOSTERS
EFFECT OF INCREASED LENGTH & DIAMETER

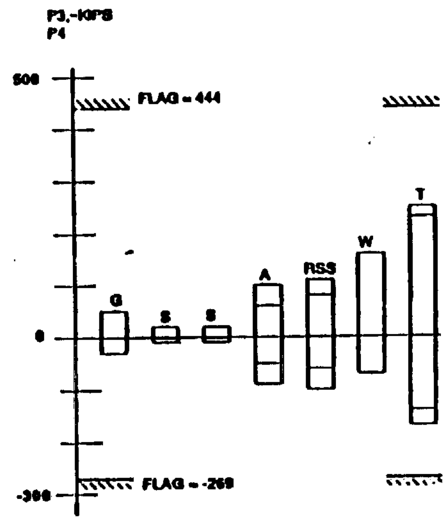
- PAST STUDIES HAVE SHOWN - THE MAJOR LOAD CONSTRAINTS IN THE MAX q REGION
  - ORBITER WING
  - FITTINGS- FT01, FT06
  - MEMBERS P_1 , P_2 , P_3 , P_4 , P_5 , P_6 , P_7

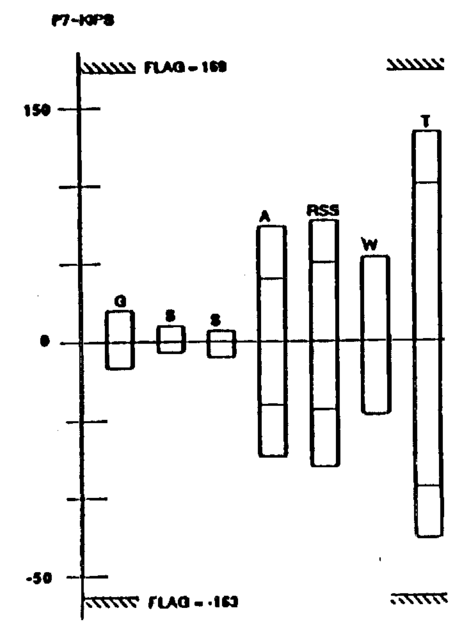


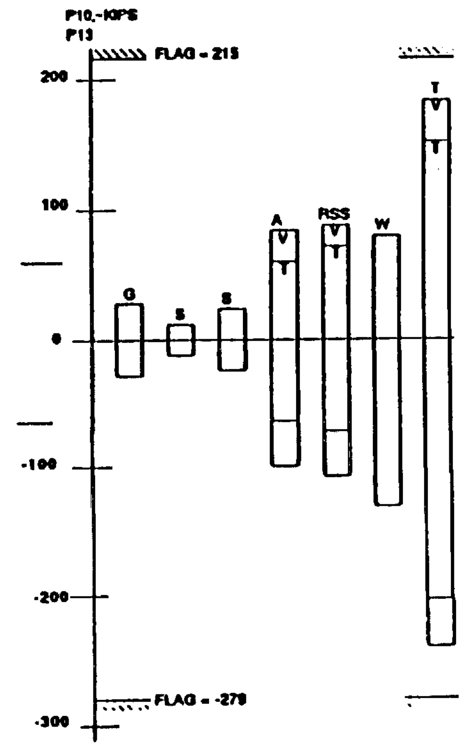


EFFECT OF AERODYNAMICS ON MAX q - LOAD CONSTRAINTS - MEMBERS



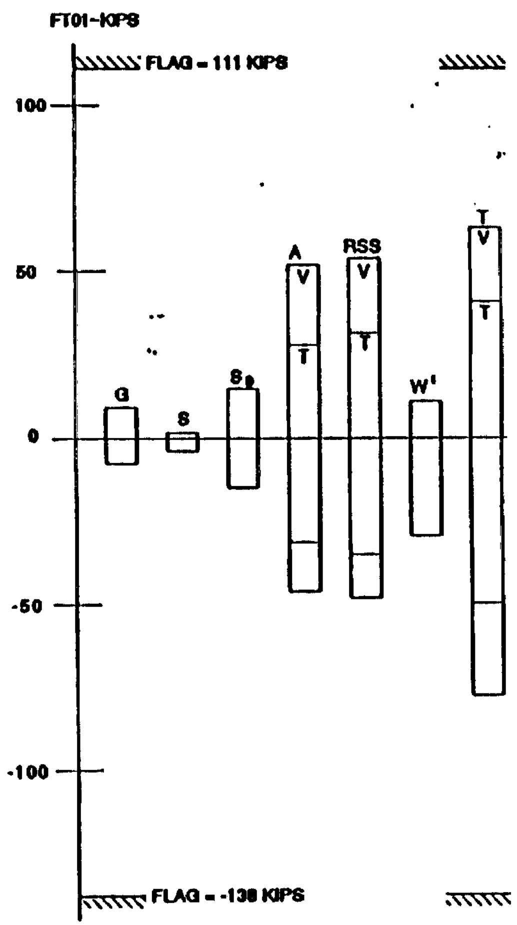


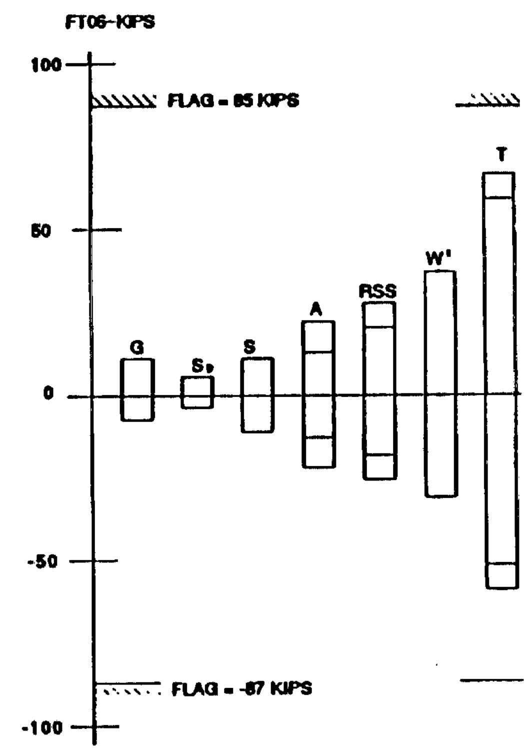




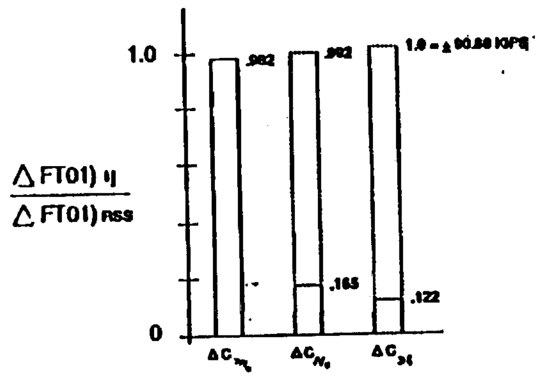
MEMBERS CAN BE EASILY FIXED

EFFECT OF AERODYNAMICS ON MAX q - LOAD CONSTRAINTS - FITTINGS

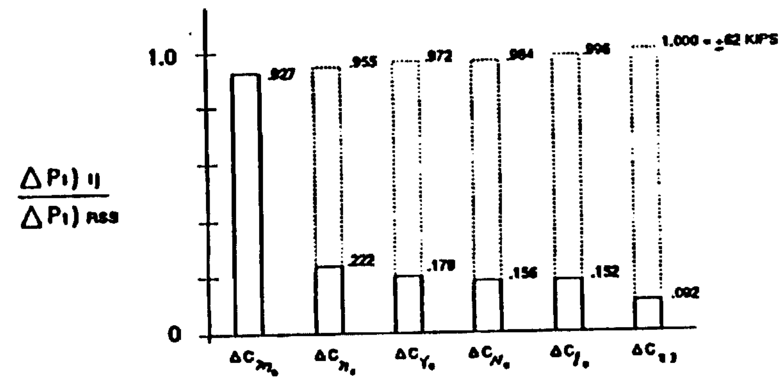




COMPONENT EFFECT ON THE AERODYNAMIC CONTRIBUTION TO THE MAX q LOAD CONSTRAINT

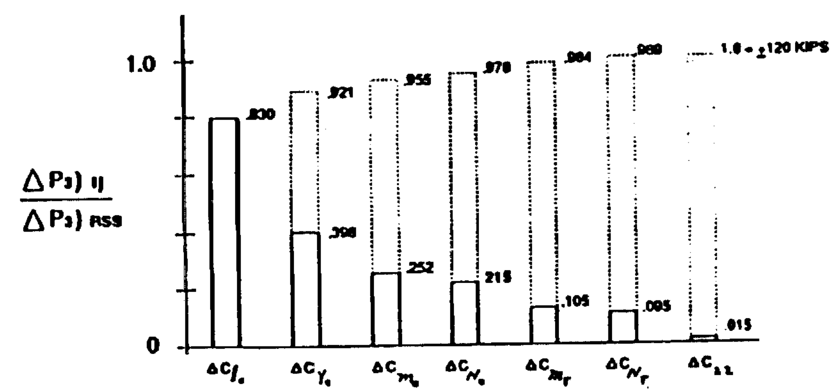


RIGID BODY FLAG LOAD = +111, -138 KIPS



ΔC = RSS OF REMAINING 23 AERO VARIATION CONTRIBUTORS

RIGID BODY FLAG LOAD = +117, -121 KIPS

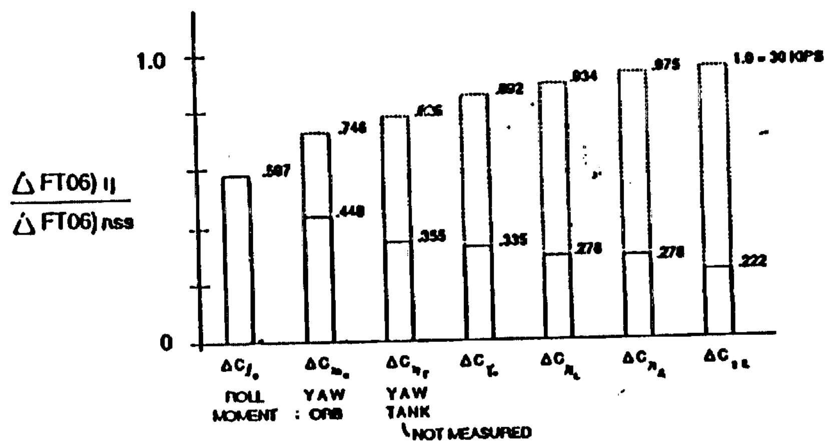


RIGID BODY FLAG LOAD = +444, -269 KIPS

ORBITER -
PITCHING MOMENT Cmo
PRIMARY CONCERN

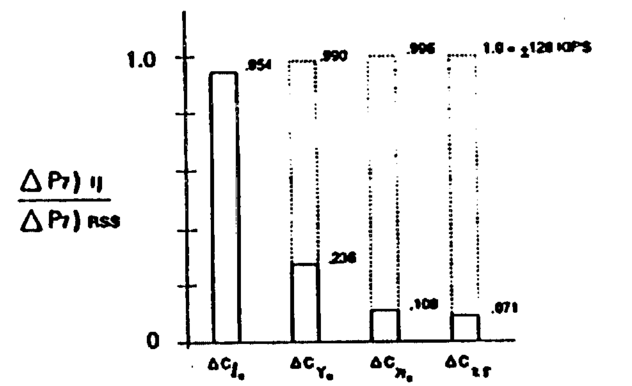
COMPONENT EFFECT ON THE AERODYNAMIC CONTRIBUTION TO THE MAX q LOAD CONSTRAINT

M = 1.15, Q = 650



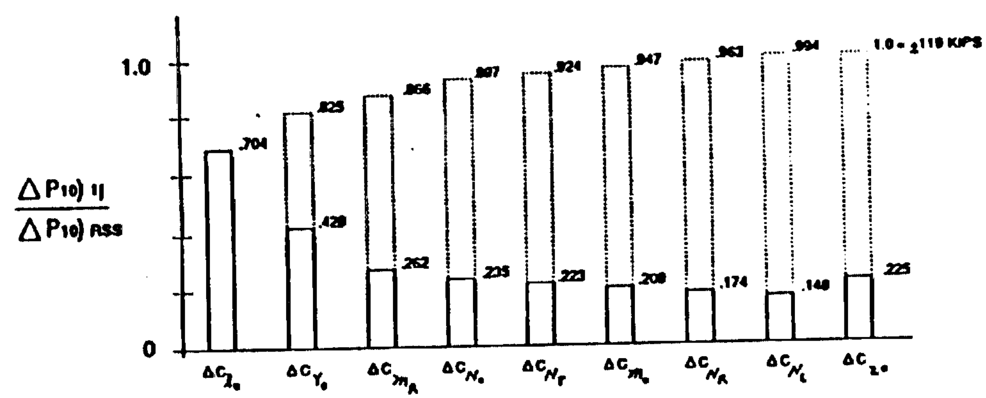
RIGID BODY FLAG LOAD = +85, -87 KIPS

M = 1.15, Q = 650



RIGID BODY FLAG LOAD = +117, -121 KIPS

M = 1.15, Q = 650

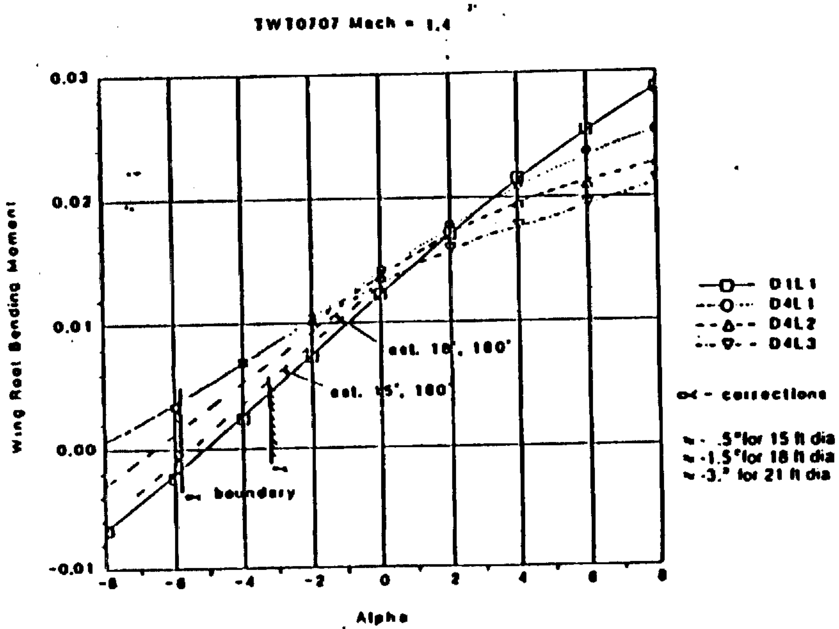


RIGID BODY FLAG LOAD = +215, -285

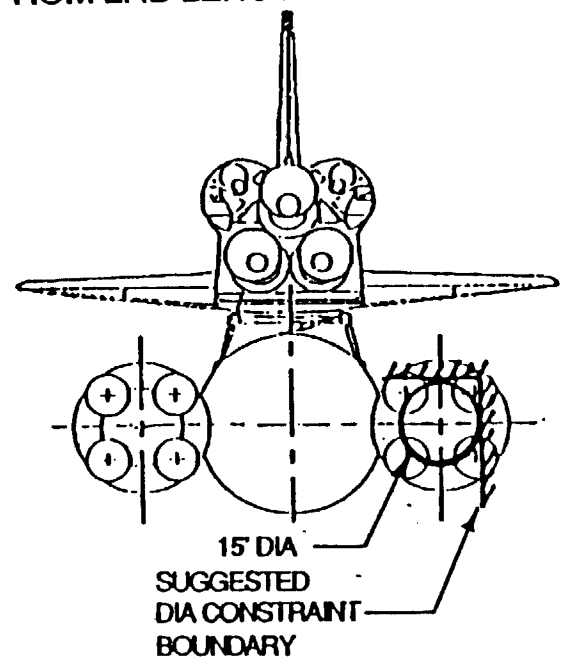
ORBITER -
PITCHING MOMENT Cmo
PRIMARY CONCERN

EFFECT OF LRB LENGTH AND DI. INCREASE ON MAX q LOADS

- THE PRIMARY CONCERNS
  - ORBITER WING LOADS
  - ORBITER PITCHING MOMENT
  - ORBITER ROLLING MOMENT (MINIMUM)



- MSFC TEST SHOWED SIGNIFICANT EFFECT ON THE ORBITER AERODYNAMICS DUE TO LRB DIAMETER CHANGES BUT NO MAJOR EFFECTS FROM LRB LENGTH



- CONCLUSION - LIMIT TANK DIAMETER THAT BRINGS LRB NO CLOSER TO ORBITER THAN AN EQU ELEMENT 15FT DIA SRB

EVALUATIONS OF CONFIGURATION FROM MAX q - CONSIDERATION

- OPTION 1
  - THE RECOMMENDED MAX 15' DIAMETER CONSTRAINT SHOULD BE APPLIED TO THE HAMMER-HEAD - UNLESS WIND TUNNEL DATA IS OBTAINED

- OPTION 2
  - STRAKES ARE NOT RECOMMENDED AS A METHOD TO ALLOW LRB DIAMETERS GREATER THAN 15' UNLESS WIND TUNNEL DATA IS OBTAINED

- OPTION 3
  - INCREASING THE ORBITER INCIDENCE ANGLE IS NOT RECOMMENDED DUE TO PAYLOAD BAY DOOR STRUCTURE LOAD AT NEGATIVE ANGLE-OF-ATTACK.

- OPTION 4
  - LOOKS REASONABLE FOR AERO LOADS AT MAX q

- OPTION 5
  - LOOKS REASONABLE FOR AERO LOADS AT MAX q
    - ADDITIONAL DATA WILL BE REQUIRED ON LOX TANK
    - MORE FORWARD CENTER OF PRESSURE CAN BE HANDLED BY FLIGHT CONTROL SYSTEM

- OPTION 6
  - SHOULD NOT ADVERSELY EFFECT THE MAX q WING LOADS

- OPTION 7
  - SHOULD NOT ADVERSELY EFFECT THE MAX q WING LOADS

- OPTION 8
  - SHOULD BE ACCEPTABLE FROM MAX q LOADING